

ACCELERATED TESTING OF CONCRETE DURABILITY
EXPOSED TO A MARINE ENVIRONMENT

by

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ABSTRACT

This report describes the development of an apparatus for the "accelerated" study of the durability of concrete which is exposed to a simulated marine environment. The test consists of a six-hour cycle (four cycles per day) of alternate wetting and hot air drying. Measurements, which included visual inspection, weight, density, volume, resonant frequency, velocity of sound, and corrosion potential, were recorded for specimens from three different mixes. After 975 cycles the responses of different mixes were easily distinguished. The results from the accelerated durability test are similar to the results from long-term exposure to the natural environment. The apparatus permits more rapid assessment of concrete durability than was previously possible.

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NOMENCLATURE

K_{sp}	- solubility product
K_w	- dissociation constant for water
$[\]$	- concentration term in mole/ litre
P_{O_2}	- partial pressure of oxygen
$\bar{C}$	- normalized chloride concentration
C_i	- initial chloride concentration
C_∞	- chloride concentration of solution
C	- minimum chloride ion concentration required to induce corrosion
$\bar{r}$	- normalized radius
r_0	- radius of cylinder
r	- radius of steel reinforcement bar
J_0	- Bessel function of order zero
J_1	- Bessel function of order one
λ_n	- eigenvalues
θ	- normalized time variable
I_m	- metal dissolution current
I_{so}	- electronation current
I_{CORR}	- corrosion current
IR	- potential drop through the electrolyte
E_{CORR}	- corrosion potential
E_m	- corrosion potential of the electron source
E_M^*	- corrosion potential of the electron source at zero current
E_{so}	- corrosion potential of the electron sink

E_{so}^*	- corrosion potential of the electron sink at zero current
$E_{O_2}^0$	- standard half cell reduction potential for $\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$
E_{Fe}^0	- standard half cell reduction potential for $Fe^{+2} + 2e^- \rightarrow Fe$
R	- gas constant
T	- absolute temperature
F	- Faraday's constant
z	- number of electrons being transferred
E^0	- standard potential of SCE vs SHE
$\hat{y}$	- response variable matrix
$\hat{x}$	- coded test parameter matrix
$\hat{\beta}$	- estimated parameter coefficient matrix
V	- volume
ρ_w	- density of water
W_A	- weight in air
W_w	- weight under water
ρ	- density of concrete
v	- velocity
K	- constant incorporating Poisson's ratio
ν	- dynamic Poisson's ratio
E_d	- dynamic modulus of elasticity
L	- length
t	- transit time
C	- constant for particular specimen
T	- correction factor
a,b	- cross sectional dimension, "a" being the direction which the prism is being resonated

n	- resonant frequency
n_1, n_2	- number of measurements to be averaged
ν_1, ν_2	- degrees of freedom
$\bar{Y}_1, \bar{Y}_2$	- sample averages
μ_1, μ_2	- sample means
S_1, S_2	- standard deviation of samples
S_p	- pooled standard deviation
t	- standard t-distribution
α	- level of significance

CHAPTER 1

1.0 INTRODUCTION

The use of cement as a jointing medium in masonry structures has been evident since the dawn of civilization. The early Egyptians burned impure gypsum to produce a product that they combined with sand and water and used the mixture to cement blocks of stone together.

The Greeks, and later the Romans, burned limestone to produce quick lime. This quick lime was slaked (moistened), mixed with sand, and used as a cementing mortar. Both the Greeks and Romans were aware that the addition of finely ground volcanic deposits increased the strength of mortar and its resistance to both fresh and salt water. Examples of Roman construction still exist today displaying the success of their building materials and construction techniques.

After the fall of the Roman Empire and through the Middle Ages the quality of cementing materials and construction techniques suffered. The cause of this decline appears to have been the poor burning of limestone and the ineffective mixing of materials. This trend was slowly reversed around the eleventh century when greater care in preparation and construction were once again followed. Throughout these periods the basic methods and materials remained constant.

The first significant advance was achieved by John Smeaton, who was employed in 1756 to rebuild a lighthouse which had burnt on Eddystone Rock of the Cornish Coast. Smeaton recognized that the addition of a clay to the limestone would result in a mortar which would harden (set) under water. Despite Smeaton's success with hydraulic cement the traditional lime mixture remained dominant. It was not until

1796 with the development of Roman cement that hydraulic cement gained a wider acceptance. This cement was manufactured by calcining (oxidizing through burning) nodules of argillaceous limestone.

Louis J. Vicat developed a hydraulic cement by calcining a mixture of limestone and clay ground together in a wet mill (circa 1810). A patent for cement of this type was taken out by James Frost in 1811.

The next major development was that of Portland cement. While the exact details of the development of Portland cement are unclear, the credit is generally given to Joseph Aspdin. A patent for Portland cement was issued to Aspdin in 1824. This material is manufactured by crushing and calcining limestone. The lime is then mixed with clay and ground, while wet, to a fine slurry. The slurry is calcined a second time to dispell carbon dioxide and water. The product is then reground to a fine powder and is ready for use as cement.

Portland cement has remained dominant to this day. Standards set by various learned societies on the production and use of Portland cement have significantly improved both its consistency and quality. Other developments have resulted in specialized cements and concretes for a variety of applications. These include low heat, rapid hydrating, and sulfate resistant cements, as well as lightweight and prestressed concretes.

Concrete is an excellent building material which is made from inexpensive raw materials and requires a minimum of processing. Cement is the greatest single cost component of concrete and can amount to 45% of the selling price of the fresh concrete.

The diverse properties of ordinary Portland cement and its derivatives make concrete a favoured and extensively used building material. In order to obtain a desired property for a particular cement it may be necessary to observe special manufacturing, mixing, and/or placing techniques, however, the same basic cement/aggregate/water mixture remains unchanged.

Concrete can either be cast in place on site or precast into members and then hauled to the site. Steel reinforcing bars can be included in concrete to enable it to act in tension. The resistance of certain concretes to freeze/thaw cycles and to fresh or salt water allows the use of concrete in harsh outdoor climates. Colourful aggregates and surface variations make concrete a decorative material, further adding to its usefulness and popularity.

With such a wide array of properties, concrete is used extensively for a diverse range of applications. The main structural applications of concrete lie in building construction, bridges, wharves, and dams. Attempts have also been made to use concrete in the construction of ship hulls (the Selma, 6340 tonnes, 1919; the Armistice, 1150 tonnes, 1919; and countless others during both World Wars)¹, railway ties, containment buildings for nuclear reactors, and offshore drilling platforms.

Concrete is indeed a very widely used and useful material but it is also subject to deterioration. Hardened cement paste is susceptible to chemical attack by ions found in seawater and de-icing chemicals. Furthermore, atmospheric carbon dioxide will neutralize

cement paste. Corrosion of steel reinforcement can cause internal expansive forces resulting in cracking and spalling of concrete.

These modes of deterioration may require decades before any significant effect is observed. Concrete should remain sound; however, in practice concretes do not always fare as well as expected if exposed to harsh climatic conditions. Deterioration and failure occasionally occur in a relatively short period of time. The marine terminals in Saint John are a case in point; here repairs have been required after only a few years of service.² Such a performance record is clearly unsatisfactory and provides the impetus for this study of the deterioration of concrete exposed to a marine environment.

Since the actual deterioration of concrete may take decades to occur, standard methods of studying this deterioration may take decades for significant results to appear. This is not acceptable considering today's urgent need for design information and an accelerated test procedure. The purposed of this study is to devise an apparatus which will cause concrete to deteriorate as it does in the field, but at an accelerated rate.

CHAPTER 2

2.0 A REVIEW OF CONCRETE PROPERTIES

2.1 PORTLAND CEMENT

Portland cement has four major constituents. These are C_3S , C_2S , C_3A , and C_4AF as defined in Table 1. The proportions of these constituents in the five main types of commercial Portland cement are given in Table 2.

Type 10, normal, cement is the industry standard. The constituent proportions and resulting characteristics of Type 20, moderate, cement are between those of normal cement and high early strength cement. See Table 2.

Type 30, high early strength, cement contains a high proportion of the rapidly hydrating C_3S species and a lower proportion of the slower hydrating C_2S specimen. The drawback of this cement is that the heat of hydration of C_3S is nearly double that of C_2S . The heats of hydration are presented in Table 3.

Although a high heat of hydration may not pose any difficulty and in fact may be desirable (e.g. in cold weather), this heat may be detrimental due to thermal expansion and cracking. To offset this problem Type 40, low heat of hydration, cement has also been developed. Here a lower proportion of C_3S is incorporated. See Table 2 and 3.

Cement Types 10, 20, 30 and 40 are all susceptible to chemical attack by sulphates; whether these ions are found in ground water or seawater. Type 50, sulphate resisting, cement is used when sulphate

NAME	CHEMICAL FORMULA	ABBREVIATION
Tricalcium Silicate	3CaO SiO_2	C_3S
Dicalcium Silicate	2CaO SiO_2	C_2S
Tricalcium Aluminate	$3\text{CaO Al}_2\text{O}_3$	C_3A
Tetracalcium Aluminoferrite	$4\text{CaO Al}_2\text{O}_3 \text{Fe}_2\text{O}_3$	C_4AF

Table 1: Major constituents of Portland Cement³

CEMENT TYPE	TYPICAL WEIGHT PERCENT			
	C_3S	C_2S	C_3A	C_4AF
10 NORMAL	50	24	11	8
20 MODERATE	42	33	5	13
30 HIGH EARLY STRENGTH	60	13	9	8
40 LOW HEAT	26	50	5	12
50 SULPHATE RESISTING	40	40	4	9

Table 2: Weight percent of major constituents in Portland Cement³

COMPONENT	HEAT OF HYDRATION (kJ/kg) ⁴	RELATIVE RATES OF HYDRATION ⁵
C_3S	500	10
C_2S	260	1
C_3A	865	16.7
C_4AF	420	2

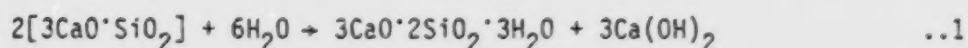
Table 3: Heats of hydration and relative hydration rates of the major constituents of Portland Cement

ions are present. Here the constituent proportions are varied so that C_3A is kept as low as possible by, in part, being partially substituted with C_4AF . When used in limited quantities C_4AF is more resistant to sulphate attack than C_4A . The effect of C_3S and C_2S on sulphate resistance remains unclear⁶.

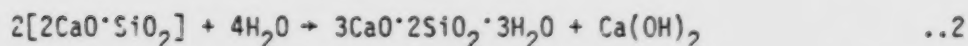
2.2 HYDRATION REACTIONS

The constituents of Portland cement are anhydrous (waterless) compounds all of which hydrate in the presence of water to form stable crystalline structures. The hydration reactions are:

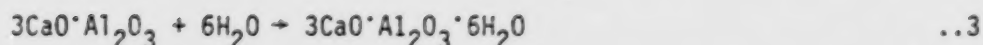
C_3S



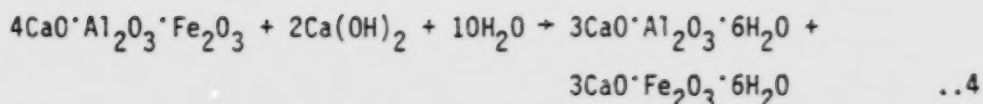
C_2S



C_3A



C_4AF

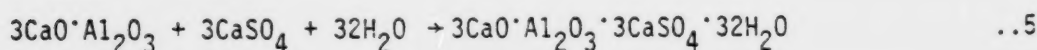


Both C_3S and C_2S react to form tricalcium disilicate hydrate and calcium hydroxide as indicated by reactions 1 and 2. The tricalcium disilicate hydrate is referred to as tobermorite gel after the naturally

occurring mineral. The formulation of calcium hydroxide during hydration causes the cement paste to become very alkaline. Typically, cement paste will have a pH of 11.5.

While the products formed by the hydration of C_3S and C_2S are the same, the rate at which these species react and the ratio of products formed are different (refer to Table 3 and reactions 1 and 2). The net effect is that the constituent C_3S/C_2S ratio has an influence on the properties of the hardened concrete.

The species which hydrates most rapidly is C_3A , as indicated in Table 3. This reaction is sufficiently rapid that an immediate stiffening, or flash set, would occur if not for the presence of anhydride (3 to 4% by weight) to retard the reaction. The reaction between C_3A and anhydride is preferential to the normal hydration reaction. The reaction between C_3A and gypsum is indicated by reaction 5.



Once all of the anhydride has been consumed to form calcium sulphoaluminate the normal hydration reaction of C_3A proceeds (reaction 3).

The C_4AF species is a minor constituent of Portland cement which consumes calcium hydroxide (a product of the hydration of C_3S and C_2S) to form a crystalline hydration product (reaction 4). Although calcium hydroxide aids the cementing effect, the loss of calcium hydroxide due to reaction with C_4AF is relatively minor. The amount of calcium hydroxide formed by the hydration of C_3S and C_2S is much greater than the amount consumed by the formation of C_4AF . This is because the

proportion of C_4AF is small relative to the amount of C_3S and C_2S (see Table 2). As noted later, this excess calcium hydroxide can react with seawater which results in the deterioration of concrete.

2.3 THE HYDRATION PROCESS

The hydration reactions described previously are simplified representations of the hydrations which actually take place. In reality the reactions proceed through a number of unstable intermediate steps which interact to form a host of products.

In 1960, T.C. Powers⁷ proposed a model of cement paste hydration. This model is supported by electron scanning micrographs and has gained a wide acceptance among experts in the field^{8,9}. The model is useful in understanding the nature of concrete and some of the factors influencing its durability.

When cement is initially mixed with water, the finely ground cement grains and water form a suspension. Since the grains are so fine and have such a high surface area ($\sim 300m^2/kg$) settling is inhibited and the cement hydrates to form a solid.

Two hours after mixing the cement mixture has become much less fluid but is still workable. Short needle-like hydration products extending outwards from the surface of the cement grains can be observed. The cement grains begin as independent particles suspended in water, but eventually start to interlock and form the basis for the hardened cement paste. By this time the water has become saturated with calcium hydroxide. The crystalline hydration products also begin to appear in the intergranular water.

Further growth of the needle-like hydration products continues. Approximately 24 hours after reaction initiation the needles have grown sufficiently long to interconnect with other needles. The interconnection of the needles of the cement grain establish the skeletal structure of the cement. By this time the interconnection is complete and continuous so that the concrete is no longer workable, but it has yet to achieve appreciable strength.

Approximately 7 days after reaction initiation the skeletal structure has been filled in by continuing hydration reactions. Although complete hydration of the cement grains has not yet occurred, the concrete has achieved considerable strength. Figure 1 indicates the strength versus time relation typical of concrete. The hydration reactions proceed at progressively slower rates with the result that complete hydration is not likely ever to be realized.

2.4 PORE FORMATION

The formation of the cement gel gives rise to a porous structure with a wide range of pore sizes. Initially all of the pores are inconnected hence the grains are simply suspended in water. As the concrete hardens, capillary pores which carry water to the surface form. Typically, capillary pores range in diameter from 8 mm to 13 μm (see Reference 11). As the cement hydrates, a needle-like structure of hydration products occur that grows out from the grain surface. The voids remaining between the needle-like hydration products are referred to as gel pores and are extremely small.

For a sample of concrete with a given volume of pores the ratio of gel pores to capillary pores affects the permeability of the

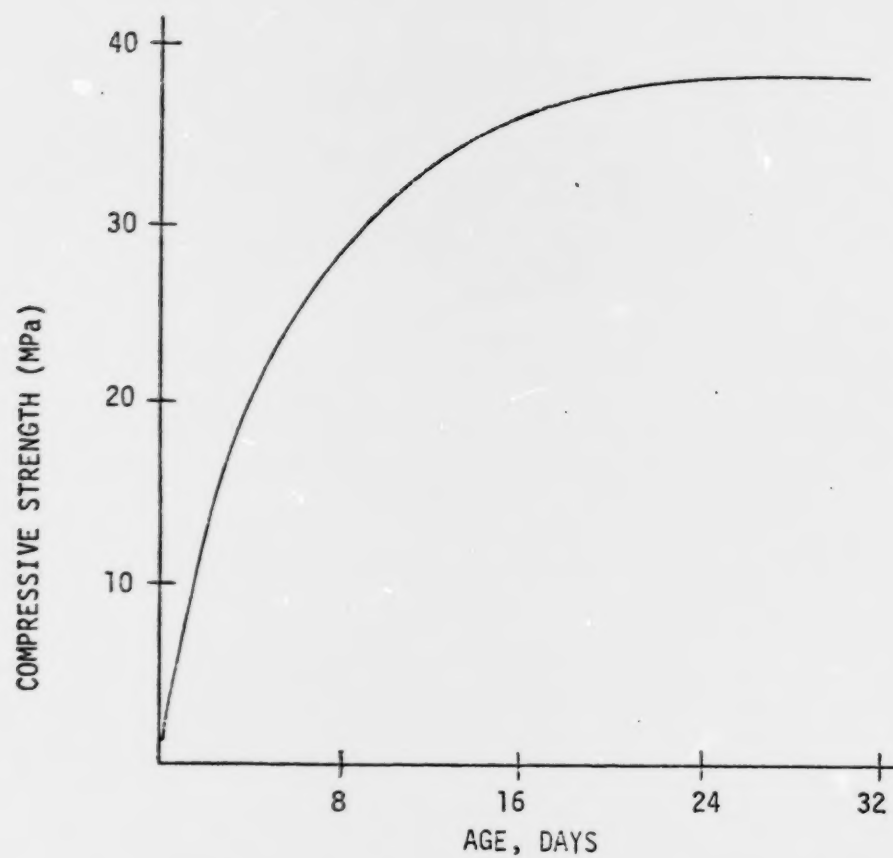


Figure 1: Typical Compressive Strength as a Function of the Time of Hydration¹⁰

concrete. Gel pores are discrete, individual voids whereas capillary pores are continuous (thus more easily allowing movement of a fluid). The result is that diffusion through the small gel pores is much more difficult than through the larger interconnected capillary pores.

Pore formation can also result through the addition of an air-entraining agent to the mixture. An entraining agent is essentially a soapy admixture which introduces voids (approx 0.5 μm) into the concrete.¹² This agent is added when the concrete will be exposed to cycles of freezing and thawing. Pores formed by entraining agents are discrete, individual bubbles with little affect on the permeability of the concrete.

2.5 WATER TO CEMENT RATIO

The hydration mechanism outlined by Powers⁷ can be used to explain the influence of the water to cement (W/C) ratio on the properties of concrete. Enough water must be added to the mixture to ensure that the cement can hydrate. Water is also needed to ensure that the mixture can be placed. The minimum water content required for complete hydration based on reactions 1 to 4 has been calculated for cement Types 10, 20, 30, 40 and 50 and is presented in Table 4. Because the concrete must be sufficiently plastic to allow placing, a W/C ratio of 0.40 or greater is required.

Increasing the W/C ratio increases the spacing between the cement grains in the initial suspension. Consequently the formulation of a skeletal structure is more difficult and less interconnection between the cement grains is achieved. The result is a structure with

more voids and therefore a weaker concrete. Figure 2 illustrates the effect of W/C ratio on the compressive strength of the concrete. The effect of W/C ratio has been extensively studied and documented^{14,15}.

CEMENT TYPE	MIN. WATER TO CEMENT RATIO (Wt. basis)
10 NORMAL	0.25
20 MODERATE	0.23
30 HIGH EARLY STRENGTH	0.25
40 LOW HEAT	0.23
50 SULPHATE RESISTING	0.23

Table 4: Minimum Water Content Required for Complete Hydration

These studies indicate that a lower W/C ratio will increase the durability and strength of the concrete.

2.6 CURING

The method used to cure concrete during initial hydration also has an influence on its durability and strength. Since the W/C ratio is a critical determinant of the quality of concrete, it is imperative that steps are taken to ensure that desiccation through evaporation during curing does not occur. Moist curing or covering concrete with an impervious membrane are two methods which are used to prevent excessive evaporation.

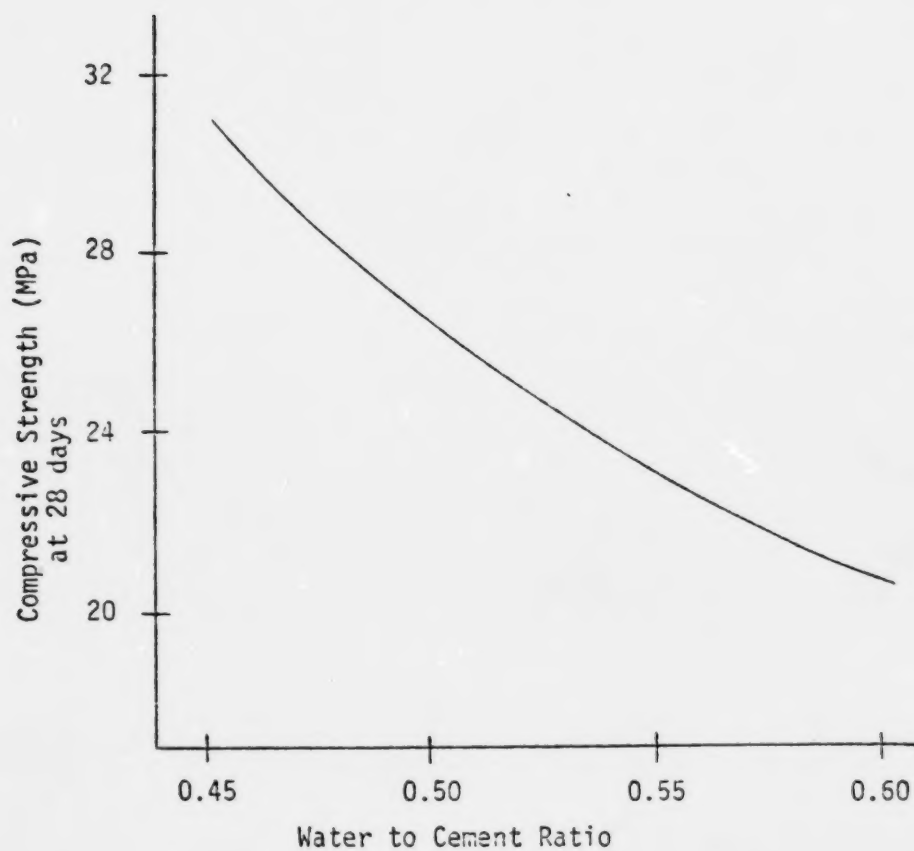


Figure 2: Typical Compressive Strength after 28 days versus the Water to Cement Ratio¹³

2.7 CEMENT FINENESS

The fineness to which the cement is ground before use is also an important factor in determining concrete quality. Large cement grains are not desirable as they do not form a homogeneous suspension when mixed with water. Large grains are also detrimental because they can decrease the degree of hydration. The hydration reaction occurs primarily at the interface between the cement grain and the water, the larger the grain the lower the surface area per unit mass and the slower the rate of reaction.

2.8 AGGREGATES

Concrete is comprised of crushed stone (aggregate) glued together with a cement paste matrix. Typically, the aggregate comprises less than 20% of the cost of placed concrete yet the aggregate is 60 to 80% of the total mass. Due to the quantity required, aggregate is usually limited to locally available sources. It is not economical to haul large quantities of aggregate over a long distance. This constraint has resulted in concrete being made with a wide range of aggregate types.

Concrete is generally comprised of two or more different sizes of aggregate--coarse and fine. The fine aggregate is sand-like in size and occupies the spaces among the larger, gravel aggregate. The result is that concrete is composed to a large extent of inexpensive aggregate material. In addition, the aggregate also provides a large surface area which the cement can adhere to. The strength of the concrete is strongly influenced by the bond between the aggregate and the cement paste and is not as dependent on the aggregate itself. This is because

in most cases the bond strength is considerably less than the strength of the aggregate, hence failure of the concrete occurs at this interface. As a consequence, aggregates of different strengths can be used successfully to produce concretes of comparable strength.

Aggregates significantly affect concrete density. Lightweight aggregates and normal weight aggregates are used to produce lightweight and normal weight concretes respectively. These concrete types are used in structures where weight considerations are important. Table 5 summarizes the effect of aggregate density on the density of the resultant concrete.

DESIGNATION	AGGREGATE		CONCRETE	
	Type	Loose Bulk Density (Kg/m ³)	Density (Kg/m ³)	Compressive Strength (MPa)
Lightweight	Pumice Expanded	700	1000	18
	Clay	400	1600	25
Normal Weight	Granite	1400	2400	35
	Limestone	1400	2400	35
Heavy Weight	Barytes	2500	3400	45

Table 5: Aggregate Density and its Relationship to Concrete Density¹⁶

Ideally, aggregates are a chemically inert filler material, however, this is not always the case. Certain aggregates contain a silica species which can react with alkaline hydroxides that arise from trace amounts of alkalis (Na_2O and K_2O) found in cement paste.¹⁷ This reaction produces an alkali-silicate compound occupying a greater volume than that of the reacting species, resulting in internal expansive forces leading to premature cracking, spalling, and failure of the concrete.

2.9 CONCRETE DETERIORATION

Concrete deterioration can occur as a result of chemical attack on the cement paste. This type of reaction mechanism takes place at or near the exposed surface. The hardened cement paste reacts with certain species found in seawater, in particular Mg^{+2} and $\text{SO}_4^{=}$ ions, and molecular CO_2 . Seawater contains relatively high concentrations of dissolved salts as Table 6 indicates. Seawater also contains trace amounts of CO_2 from the atmosphere. This amount may be enriched if the seawater is exposed to decaying organics.

Mehta¹⁸ describes the manner by which these species react with concrete. Essentially three layers of attack are formed as illustrated in Figure 3. The first layer of attack is a result of the neutralizing reaction between CO_2 dissolved in seawater and the $\text{Ca}(\text{OH})_2$ of the concrete. The reaction forms aragonite (CaCO_3) which can further react to form calcium bicarbonate ($\text{Ca}(\text{HCO}_3)_2$). The second layer of attack is a result of the reaction between Mg^{+2} ions and the concrete. The extent of this second layer is limited by the inability of the Mg^{+2} ions to

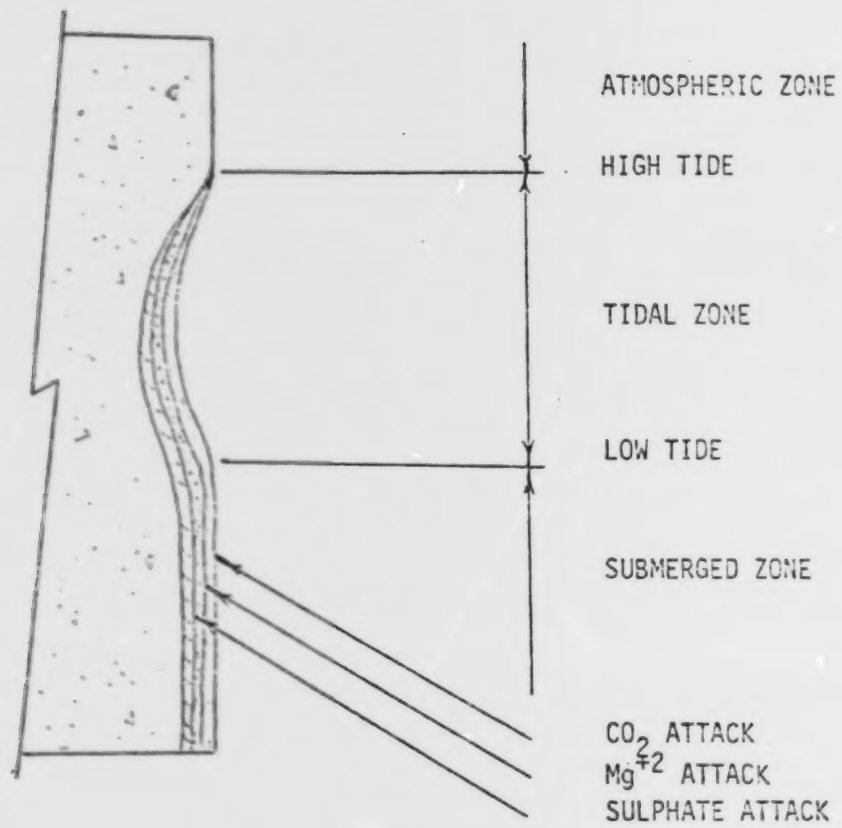


Figure 3: Deterioration of concrete in seawater¹⁹

Element	ppm (by weight)
Cl	18980
Na	10561
Mg	1272
S	884
Ca	400

Table 6: Principal elements in seawater²⁰

penetrate a region where OH^- ions are present. Only after the CO_2 has reduced the hydroxide ion content (in the first layer) can the Mg^{+2} ions diffuse into the concrete and react. The host of compounds in the concrete and the possible reaction pathways makes a detailed description of the chemical reactions very difficult. The major products which are formed in these regions are gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), ettringite ($3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 32\text{H}_2\text{O}$), and brucite ($\text{Mg}(\text{OH})_2$).

A third layer is found beyond the second and is where the sulphate ions react. Again a complex series of reactions are occurring, but results are similar. The sulphate ions react to form gypsum and ettringite.

The formation of gypsum causes the surface of the concrete to soften, furthermore both gypsum and calcium bicarbonate are soluble in seawater so they are slowly leached away. The formation of ettringite is an expansive reaction which introduces cracking and spalling of the concrete surface. Both the leaching and spalling reactions are enhanced

by erosion from wave action which results in the greatest deterioration at the mid-tide level. Mehta²¹ cites several examples of these types of deterioration. The best documented case is the concrete piles near Ocean City, New Jersey. These piles, placed in 1932, show extreme loss of surface material--reducing the piles to 300 mm from the original thickness of 550 mm after 25 years.

2.10 CORROSION OF STEEL REINFORCEMENT

Once the reactive seawater ions have penetrated the concrete, a second deterioration mechanism can be initiated. Under certain circumstances these species can induce the corrosion of the steel reinforcement. The iron oxides produced by corrosion occupy a greater volume than the original iron. This is illustrated in Table 7 which compares the volume of iron to that of its oxides on a per mole of iron atoms basis. The formation of iron oxides results in the buildup of internal expansive forces. To relieve these forces, cracks often form. The cracks tend to run parallel to, and interconnect reinforcing bars which exposes the reinforcing to further corrosion and as a result deterioration accelerates.

This type of deterioration is evident in Halifax Harbour.²³ Although pier 2 of the harbour was completed in 1913, a detailed survey conducted in 1930 indicates that many of the concrete piles and slabs were disintegrating and exposing the reinforcing steel. Repair work in the 1930's and 1940's was initiated in an attempt to halt the deterioration process. The lack of success of these early repairs was indicated by subsequent repairs in 1963 and even more recently.

SPECIES	RELATIVE VOLUME
Fe	1
Fe ₃ O ₄	2.1
Fe(OH) ₂	3.7
Fe(OH) ₃	4.2
Fe(OH) ₃ ·3H ₂ O	6.3

Table 7: Relative volumes of iron oxides²²

A second example of this type of deterioration is illustrated in Figures 4 and 5. These pictures show a section of concrete removed from the roof of a heating tunnel servicing the University of New Brunswick. The tunnel, originally built in 1964 is used to carry steam lines from the central heating plant to various campus buildings. The tunnel showed such extreme signs of spalling and cracking on the underside of the roof that extensive repairs were required in 1983-84. The corrosion of reinforcement, cracking along bars, and spalling are clearly evident in Figures 4 and 5.

The reactions given below are represented separately as the oxidation of metallic iron and the reduction of oxygen (reactions 6 and 7 respectively). These two half-cell reactions are not occurring in isolation but are occurring simultaneously in the net or overall reaction 8.

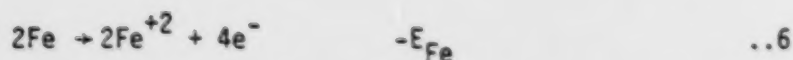
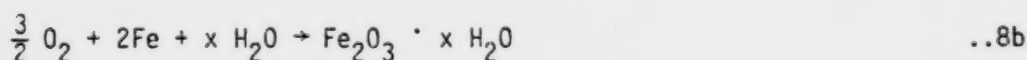
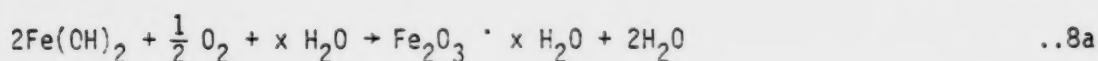
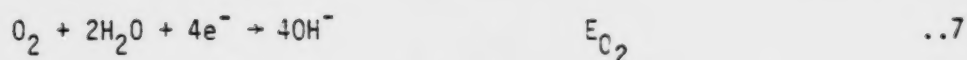




Figure 4: Underside Section of the U.N.B. Heating Tunnel
after ~ 20 years of Service



Figure 5: Closeup of U.N.B. Heating Tunnel Showing Cracking due to Steel Reinforcement Corrosion



The $\text{Fe}(\text{OH})_2$ species formed can be further oxidized in the presence of O_2 to form hydrated ferric oxide, commonly referred to as "rust," (reaction 8a). Combining reaction 8 with 8a yields the overall corrosion of metallic iron to "rust," reaction 8b.

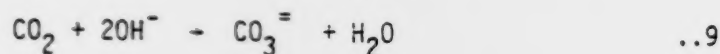
The standard free energy change at 298K for reaction 8b can be calculated as $\Delta G_{298}^\circ = -1015 \text{ kJ/mol}$. The negative value for the standard free energy change indicates that metallic iron is thermodynamically unstable in the presence of oxygen. Just as reaction 8 was the sum of reaction 6 and 7, the potential of the overall reaction is the sum of the individual half cell reactions.

The situation is complicated when steel is embedded in concrete. The transfer of the reactants and products to and from the corrosion site is impeded. Under such circumstances the formation of $\text{Fe}(\text{OH})_2$ will occur as indicated by reaction 8; however, with the immediate supply of oxygen consumed no further corrosion can occur (reaction 8a). Furthermore there is no mode of transport for the ferrous ion to a point where further oxidation can take place. In essence, the $\text{Fe}(\text{OH})_2$ species forms a passivating film

protecting the metal from continued corrosion. The very alkaline nature of hardened cement paste is also instrumental in retaining the $\text{Fe}(\text{OH})_2$ film. The high hydroxide ion concentration prevents the $\text{Fe}(\text{OH})_2$ film from dissolving thereby further decreasing the mobility of the ferrous ions.

Evidence of the formation of a passivating film in highly alkaline environments which prevents the corrosion of iron is given by Pourbaix.²⁴ Pourbaix states that at a pH of 10-13, iron is protected by alkalization (the formation of a passivating oxide film). This process applies only to solutions not containing chloride ions.

The passivating film can be destroyed or disrupted by either carbonation or chloride diffusion. In the former case atmospheric CO_2 reacts with the OH^- ions of the cement paste in a neutralizing fashion, reaction 9.



The result is a lowering of the pH and consequent destruction of the $\text{Fe}(\text{OH})_2$ film. Fortunately, the process is limited to small depths of penetration (in the order of 50 mm/year)²⁵ and can be effectively eliminated as a corrosion initiator if the reinforcement has sufficient concrete cover. The latter case, disruption of the passivating film by chloride diffusion, is of greater concern since it can initiate corrosion even if significant cover exists. Chloride ions diffuse into concrete and affect the ionic conductivity of the hardened cement paste. When chloride ions have reached the steel interface, the ferrous ions of the $\text{Fe}(\text{OH})_2$ film are mobilized and the protecting quality of the film is destroyed. Figure 6 is an attempt by Tuutti²⁶ to illustrate the manner by which chloride diffusion initiates corrosion.

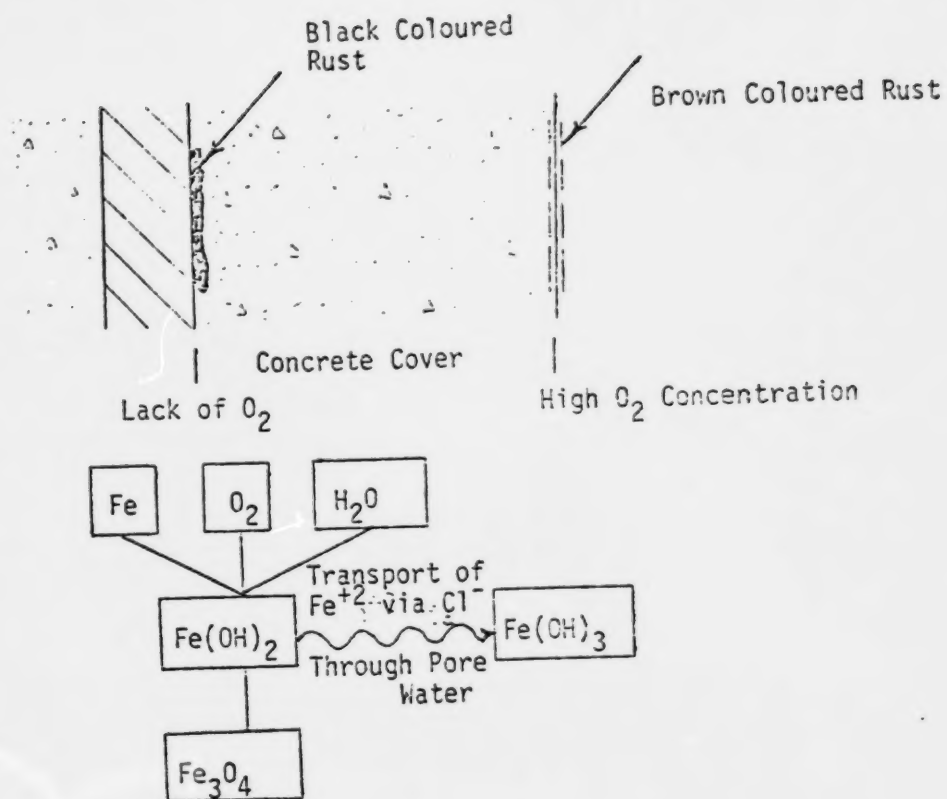


Figure 6: Chloride Initiated Corrosion²⁶

The concentration of chloride ions which is necessary to activate corrosion is dependant on the pH of the hardened cement paste. This value has been determined experimentally by Hausmann²⁷ who reports the critical value as being 0.61 for the ratio of chloride ions to hydroxide ions.

The time required for sufficient chloride ion concentrations to diffuse to the $\text{Fe}(\text{OH})_2$ film can be estimated theoretically to show the effect of pH and the diffusion coefficient. The method used to predict this time is indicated below.

The definition of the dissociation constant for water and pH are given by:

$$K_w = [\text{OH}^-] [\text{H}^+] = 10^{-14} \quad \dots 10$$

$$\text{pH} = -\log [\text{H}^+] \quad \dots 11$$

Combining 1 and 2 and solving for $[\text{OH}^-]$

yields ...

$$[\text{OH}^-] = 10^{\text{pH} - 14} \quad \dots 12$$

Based on Hausmann the minimum chloride ion concentration required to induce corrosion is...

$$[\text{Cl}^-]/[\text{OH}^-] = 0.61 \quad \dots 13$$

Substituting for $[\text{OH}^-]$ in 12 from 13 and rearranging gives...

$$[\text{Cl}^-] = 0.61 \times 10^{\text{pH} - 14} \quad \dots 14$$

Equation 14 relates the minimum chloride ion concentration required to induce corrosion to the pH of the hardened cement paste.

The chloride ion concentration as a function of position and time for unsteady-state diffusion in an infinitely long cylinder, is described by equation 15. (Refer to Appendix I for derivation and definition of symbols.)

$$\bar{c} = 2 \sum_{n=1}^{\infty} \frac{J_0(\lambda_n \bar{r})}{\lambda_n J_1(\lambda_n)} e^{-\lambda_n^2 \bar{t}} \quad \dots 15$$

The next consideration is to define the system to which a solution is desired. The cylinder chosen is 7.6 cm in radius with a steel bar 1.0 cm in radius located at the centre of the cylinder.[†] The chloride ion concentration is chosen as 0.557 mol/liter which approximates that of seawater.

The solution of the unsteady-state diffusion equation requires that both the concentration and position variables be in a normalized form. The definition and values of these variables for this particular case are outlined below.

$$\bar{r} = r/r_0$$

where

$\bar{r}$ = the normalized radius

0 = centre of cylinder

1 = outer edge of cylinder

r_0 = the radius of the cylinder = 7.6 cm

r = the position of the steel/concrete interface

$$= 7.6 - [7.6 - 1.0]$$

$$= 1.0 \text{ cm}$$

Thus

$$\bar{r} = 1.0/7.6 = 0.13$$

[†] The size of cylinder chosen reflects the actual size of test cylinders used in the experimental section, refer to Appendix II.

where

$$\bar{C} = \frac{C_i - C}{C_i - C_\infty}$$

$\bar{C}$ = the normalized chloride concentration

C_∞ = the chloride concentration of the solution in which the cylinder is to be immersed = 0.557 mol/liter.

C_i = the initial chloride concentration of the concrete
0 mol/liter

C = is the minimum chloride ion concentration required for corrosion activation.

The value of C is calculated from equation 14 for four different pH values typical of hardened cement paste. These values as well as the normalized chloride ion concentrations are presented in Table 8. The remaining parameter which must be estimated is the diffusion coefficient for chloride ions in cement paste. The diffusion coefficient can be obtained from published work by Bakker²⁸. The value is dependent on both the W/C ratio and the time of curing. Bakker's diffusion coefficient data for normal Portland cement are presented in Table 9.

An estimation of the time required to reach minimum chloride ion concentration to activate corrosion can now be made. This is accomplished by evaluating equation 15 for various times and diffusion coefficients and finding values to give the desired concentration of chloride outlined in Table 8. The results from these calculations are

pH	$C=[Cl^-]$ mol/liter	$\bar{C}$
11.0	0.00061	0.0011
11.5	0.0019	0.0034
12.0	0.0061	0.011
12.5	0.019	0.034

Table 8: Minimum Chloride Ion Concentration Required to
Activate Corrosion

Time of Curing (days)	W/C Ratio	Diffusion coefficient (10^{-8} cm ² /sec) ²⁸
5	0.50	5.08
28	0.55	3.57
28	0.60	6.21
28	0.65	8.53
60	0.50	4.47
103	0.50	2.96

Table 9: Diffusion Coefficient for Chloride Ions
Through Hardened Cement Paste

tabulated in Table 10 and presented graphically in Figure 7. The results show clearly that the time required for sufficient chloride ions

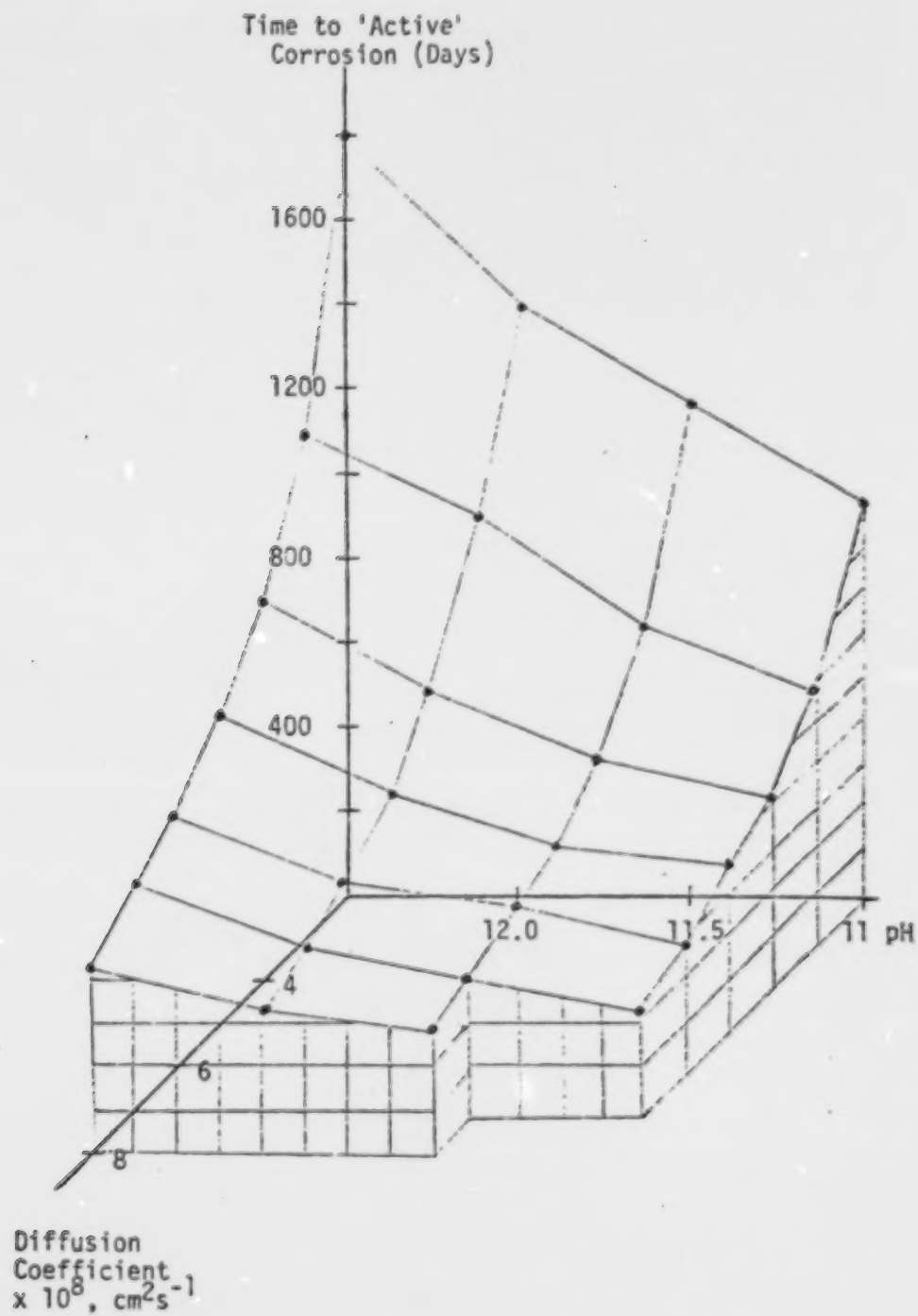


Figure 7: Predicted Time to "Active" Corrosion vs pH and Diffusion Coefficient

to diffuse to the steel/concrete interface to activate corrosion is dependent on both the pH and on the diffusion coefficient. These factors are dependent on the nature of the concrete.

Diffusion Coefficient ($\times 10^{-8}$ cm ² /sec)	Days Required to Reach Minimum Chloride Concentration at			
	pH=11.0	pH=11.5	pH=12.0	pH=12.5
2	950	1200	1400	1800
3	600	750	1000	1200
4	450	550	700	900
5	400	450	550	750
6	300	400	450	600
7	250	350	400	550
8	-	250	350	450

Table 10: Time Required to Reach Minimum Chloride Concentration
Required to Activate Corrosion

2.11 CORROSION POTENTIAL MEASUREMENT

Corrosion of steel reinforcement embedded in concrete may be monitored through the measurement of the corrosion potential or mixed potential of the steel.

Corrosion of steel in an alkaline environment occurs through the combination of two half cell reactions (as will be discussed). The first reaction produces a current of electrons through metal dissolution I_M , while the second consumes electrons through electronation, I_{SO} . The flow of electrons produced at the electron source is equal to, but opposite in direction to, the flow at the

electron sink. Furthermore, the rate of corrosion is equal to the rate at which metal dissolution is occurring.

$$\text{Thus, } I_{\text{CORR}} = I_M = I_{\text{SO}}$$

In the corrosion process the electron sink and the electron source are short circuited since metal dissolution and electronation are occurring on the same piece of material. As a consequence the potential difference across the corrosion cell is zero. The zero potential is a difference between the potential at the electron sink, E_{SO} , and the electron source, E_M , plus the addition of any IR drop in the electrolyte.

$$\text{That is, } 0 = E_{\text{SO}} - E_M + IR$$

Just as the rate of corrosion is equivalent to the metal dissolution current, the corrosion or mixed potential is equivalent to the potential of the electron source, providing the IR drop can be neglected.

$$\text{Therefore, } E_{\text{CORR}} = E_M = E_{\text{SO}}$$

Corrosion of steel reinforcement in concrete is expected to occur via local cell action, because heterogeneity exists on the metal surface of the steel (e.g. stress concentrations, ion concentrations and metal impurities). This produces areas preferential to either electronation or de-electronation (metal dissolution). The physical separation between these areas should, however, be extremely small and consequently the current path through the electrolyte is short. Thus the simplifying assumption that $IR \approx 0$ can be made. The validity of this assumption is dependant on the criterion that ionic conductivity (reciprocal of resistance) of the electrolyte solution is high. This

situation is expected once sufficient chloride ions have diffused to the metal surface and destroyed the highly resistant oxide film.

The corrosion potential can be indicated on an Evans diagram, Figure 8²⁹. This diagram depicts the potential of the two half cell reactions as a function of current superimposed on the same set of axes. The corrosion current is the current where the electronation and de-electronation currents are equal, as indicated by the intersection of the two curves. This point of intersection also defines the corrosion potential since the potential of the two processes are equivalent here.

Exact description of the potential-current curves is difficult without resorting to experimentation; however some semi-quantitative information can be obtained by examining the Evans diagram. Firstly, the open circuit potentials of the half cells (at zero current) can be obtained from the Nernst equation. This is illustrated by equations 16 and 17.

$$E_{so}^* = E_{O_2}^{\circ} + \frac{RT}{FZ} \ln \frac{P_{O_2}^{\frac{1}{2}}}{[OH^-]^2} \quad \dots 16$$

$$E_M^* = E_{Fe}^{\circ} + \frac{RT}{FZ} \ln [Fe^{=2}] \quad \dots 17$$

where

$E_{O_2}^{\circ}$ and E_{Fe}° = the standard potential

R = gas constant = $8.314 \text{ JK}^{-1} \text{ mol}^{-1}$

T = absolute temperature = 298.15 K

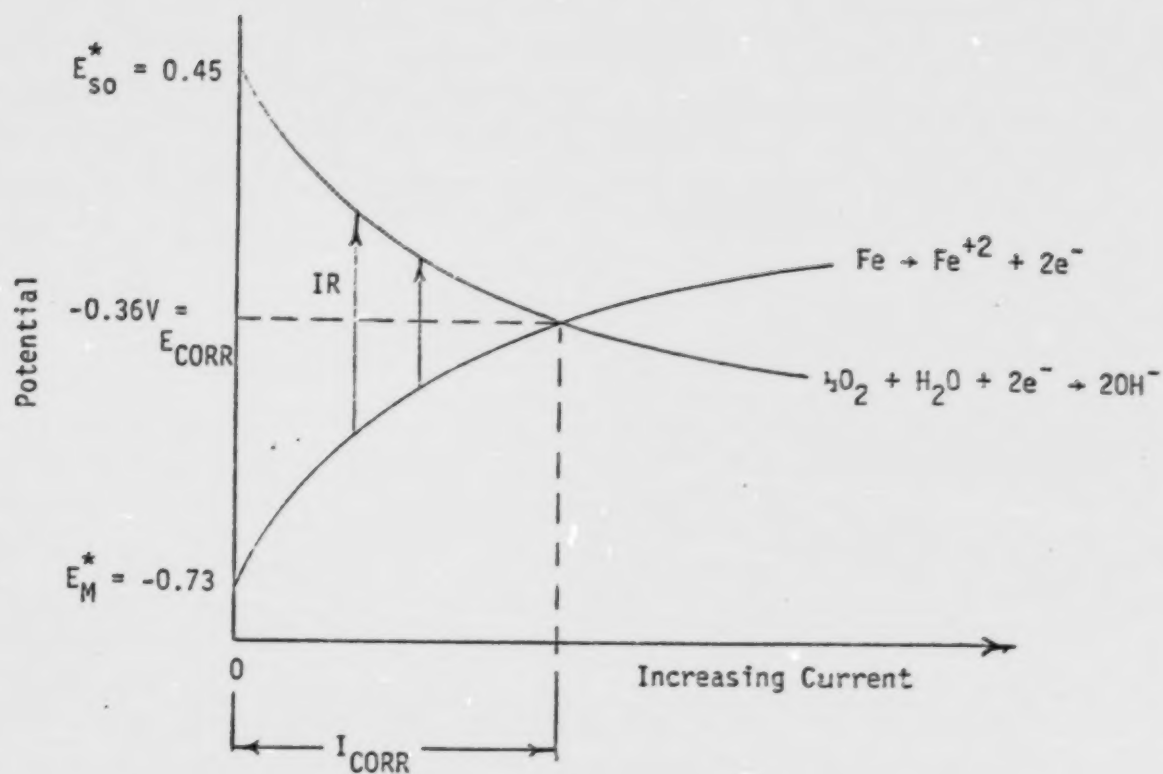


Figure 8: Evans Diagram, Potential vs. Current²⁹

F = Faraday's constant = $9.648 \times 10^4 \text{ C mol}^{-1}$

Z = number of electrons being transferred.

The solubility product of $\text{Fe}(\text{OH})_2$ is given by:

$$K_{sp} = [\text{Fe}^{+2}] [\text{OH}^-]^2 = 1.64 \times 10^{-14} \text{ mol}^3/\text{liters}^3 @ 18^\circ\text{C}^{30}$$

Making use of the solubility product and equation 12, the Nernst equations for each half cell can be calculated as a function of the partial pressure of O_2 and the pH of the cement paste (equations 12 and 19 respectively).

$$E_{so}^* = 0.814 + 0.0128 \ln P_{\text{O}_2}^{\frac{1}{2}} - 0.0295 \text{ pH} \quad \dots 18$$

$$E_M^* = -0.440 + 0.0128 \ln [1.64 \times 10^{2(7-\text{pH})}] \quad \dots 19$$

Now assuming a pH of 12 and a partial pressure of 0.21 atm for O_2 [†], the open circuit potentials of the half cells become:

$$E_{so} = 0.450 \text{ V} \quad E_M = -0.728 \text{ V}$$

The potential of the half cell reactions at zero current are shown in Figure 8.

The presence of the passivating $\text{Fe}(\text{OH})_2$ film can be indicated on the diagram by including the IR drop across the electrolyte on the Evans diagram. This is indicated in Figure 8 by vertical lines between the potential-current curves. As the IR drop increases, I_{CORR}

[†] E_{so} is not strongly dependent on the partial pressure of oxygen at $P_{\text{O}_2} = 10^{-6} \text{ atm}$, $E_{so} = 0.37 \text{ V}$ versus standard hydrogen electrode.

decreases. The decrease in I_{CORR} implies that the rate of corrosion is decreasing, thus the presence of the $Fe(OH)_2$ film acts to pacify the metal.

The corrosion potential and consequently the corrosion process are influenced by difficulties in oxygen transfer to the corrosion site. The effect of oxygen mass transfer resistance on the corrosion potential is illustrated in an Evans diagram in Figure 9³¹. The electronation current is limited by the lack of oxygen at the corrosion site, as indicated in the Evans diagram by a vertical slope of the potential-current curve for the oxygen reduction reaction. The result is that both the corrosion potential and corrosion current (and hence corrosion rate) are lowered. As oxygen transfer becomes increasingly difficult, the limiting current progressively decreases in magnitude. This further decreases both the corrosion potential and corrosion current.

Studies conducted by Hill, Spellman, and Stratfull^{32,33} show that a measured potential of 0.05V versus the standard hydrogen electrode (SHE) indicates that the steel reinforcement is in a passive state whereas a measured potential of -0.12V versus SHE indicates a condition conducive to corrosion. Their studies also show that the values follow a normal statistical distribution in which a measured potential less than 0.02V versus SHE represents a 95% limit of confidence that a state conducive to corrosion exists.

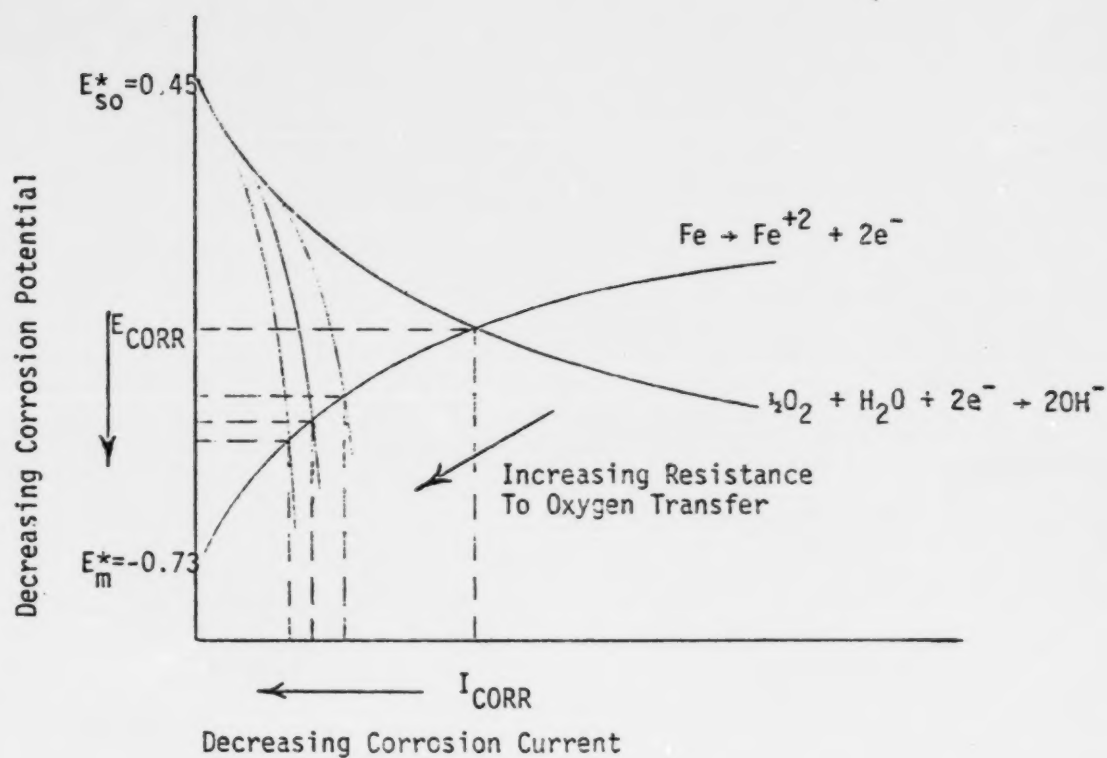


Figure 9: Evans diagram depicting the effect of increasing oxygen mass transfer resistance³¹

CHAPTER 3

3.0 REVIEW OF ACCELERATED TESTING METHODS

The use of accelerated tests to estimate the long term durability of concrete exposed to a marine environment has not been exploited to its full potential. Studies conducted by Nishibayashi et.al.³⁴ and by Kasai and Nakamura³⁵ are the most comprehensive work in this area. In both cases the investigators attempted to simulate field exposure conditions through wet/dry cycles. Nishibayashi et. al. exposed prismatic specimens (10x10x40 cm) first to immersion in seawater for 24 hours and then to drying in an oven (60 to 80°C) for 24 hours. This test was continued for 200 cycles with periodic measurements of the relative dynamic modulus of elasticity and specimen length changes.

Kasai and Nakamura used small specimens measuring 4.0x4.0x16.0 cm. These specimens were exposed to cycles of hot air drying (80°C) and then to wetting with substitute seawater. This test was conducted for 160 cycles with periodic measurements of the dynamic modulus of elasticity and weight changes.

Both sets of investigators observed that detectable changes had occurred over the course of the experiment. The studies by Kasai and Nakamura, however, were limited to mortar specimens as opposed to concrete specimens. The validity of comparing small mortar specimens to in-situ concrete is questionable. Nishabayashi and his co-workers did employ larger concrete specimens for their investigations, however, based on 2 days per cycle for 200 cycles their test required a period of 400 days. In addition neither set of investigators were concerned with the effect of steel reinforcement corrosion on specimens.

Visvesvaraya and Mullick³⁶, and Samarin³⁷ proposed that accelerated durability studies be concerned with a cyclic wetting and drying procedure but do not report any experimental data.

Other work has been conducted by experimenters, but is limited to simple procedures which are not representative of field exposure conditions of interest to this study. Bosch³⁸, and Guyot³⁹ used a continuous immersion test in a high salt content solution. These accelerated tests are of considerable duration; from 1 year in the case of Bosch's test to 2-3 years for Guyot's test. Still other techniques such as an increased surface area to volume ratio (conducted by George⁴⁰ requiring 5 years of exposure) and increased pressure (conducted by Krishnamoorthy⁴¹) have been attempted.

Studies on corrosion of steel reinforcement have also been investigated and accelerated test procedures developed. In studies by Hill et.al.⁴² and Spellman and Stratfull⁴³ the corrosion was accelerated by immersing the concrete specimen containing the steel reinforcement in a saturated salt solution. A second method used to induce corrosion was developed which applied a potential to the steel bar. T.J. Larsen and co-workers⁴⁴, and Hartt and Brown⁴⁵ found that corrosion could be induced in this manner.

None of these accelerated procedures resemble field conditions which would be encountered by marine concrete. Furthermore, it would be much more beneficial if the rate of deterioration of concrete specimens could be accelerated to a much shorter period than has been attained in the past.

CHAPTER 4

4.0 EXPERIMENTATION

4.1 CONCRETE MIXES

In order to evaluate the effectiveness of the accelerated durability test it was deemed necessary to determine if the test could distinguish between a poor quality concrete and a good quality concrete. Furthermore, it was also desirable to choose mixes which are identical to those undergoing long term marine exposure tests at Treat Island, Maine⁴¹. In this way some comparison between the accelerated durability test and actual field exposure would be possible. Concrete mixes with a low and a high W/C ratio were used as the good and poor quality mixes respectively. The good quality mix has a W/C ratio of 0.40, while the poor quality mix has a W/C ratio of 0.60. A third mix of a somewhat controversial durability was also chosen. This mix contained a W/C ratio of 0.60 together with 65% of the cement being replaced with slag. The controversy arises between the European community, which has favoured the use of a slag constituent since early in the century^{47, 48} and the Americans who in the past have been reluctant to use slag.

The details of the mixes and of the size and shape of the specimens can be found in Appendix II.

4.2 PRELIMINARY INVESTIGATION

4.2.1 Introduction

In order to best determine which exposure parameters may be significant to the deterioration process, a simple statistical experiment was performed. The results from this preliminary experiment were used in designing the accelerated test in its final form.

The five exposure parameters identified for the preliminary study are outlined in Table 11. Chemical reactions and their corresponding rates are enhanced by increased temperature and increased concentrations of the reacting species. For this reason immersion temperature and increased salt concentration were identified as possible parameters which would affect the rate of deterioration.

-
- i- Immersion temperature
 - ii- Wet/dry cycling
 - iii- Partial immersion
 - iv- Increased salt concentration
 - v- Decreased pH

Table 11: Exposure Parameters Examined in Preliminary Study

Secondly, the choice of partial immersion and wet/dry cycling as parameters stems from the observation that the location of greatest deterioration of in-situ concrete structures occurs at the mid-tide

level. These two parameters are simplistic attempts to simulate this exposure condition. The wet/dry cycle also incorporates drying at a temperature higher than the immersion temperature in order to create a thermal shock affect on the specimens.

Since concrete is typically basic ($\text{pH} > 11$), it was assumed that reducing the pH of the immersion solution might have a significant affect on the deterioration process.

4.2.2 Theory

The method of investigation chosen was a 2^{5-1} (resolution V) fractional factorial design. A detailed description of this type of experiment is given by Bacon⁵⁰. The experiment has 5 parameters each operating between a designated high (+1) and low (-1) value. For this reason this type of experiment is referred to as a 2-level design. If all variables and combinations of variables were to be considered without any overlapping information then 32 (2^5) runs would be required. While it was found that 32 runs was prohibitively large, a suitably designed experiment of 16 (2^{5-1}) runs was possible to implement and would give virtually the same information. The loss of information that occurs in shifting from the saturated 2^5 experiment to the 2^{5-1} experiment is the confounding of the estimates of single variables with that of four variable interactions ($1+4 = 5$), and two variable interactions with that of three variable interactions ($2+3 = 5$). The confounding implies that it is not possible to distinguish whether an observed effect is the result of a single variable or a combination of four variables interacting together. Similarly the effect of two variable interactions and three variable interactions cannot be

distinguished. Thus the experiment is referred to as being of resolution V. Fortunately the effects of 3 or more variables in combination are generally not contributing factors to a process and thus can be neglected. The measurements were then fitted to the following mathematical model using the least square method. This procedure is outlined by Bacon⁵⁰.

$$\hat{Y} = \hat{\beta} \hat{X}$$

Where $\hat{Y}$ is the response variable; either normalized weight loss or visual inspection number; $\hat{X}$ is the coded test parameter matrix and is composed of a 2^{5-1} fractional factorial design and $\hat{\beta}$ is the matrix of the estimated parameter coefficients as determined by a least squares fit.

4.2.3 Experimentation

Two levels of each variable were chosen based on the supposition that the difference between the high and low condition would produce a noticeable affect if the particular variable was important. The high and low conditions of the variables are summarized in Table 12.

The experiment consisted of 16 runs (performed concurrently) in which the parameters were systematically varied between their designated high and low values. The experiment consisted of a saturated 2-level design for the first four variables with the fifth parameter being varied as the combination of the first four. The design structure is given in Table 13.

The specimens were placed in 1 litre beakers containing the test solution in which the pH and temperature were monitored daily.

TEST PARAMETER	LOW CONDITION (-1)	HIGH CONDITION (+1)
X1 - Immersion temp.	20°C	50°C
X2 - Wet/dry cycling	No	Yes
X3 - Partial immersion	No	Yes
X4 - Increased salt concentration	Std salt concentration	5X Std salt concentration
X5 - pH	8.2	5

Table 12: Test Parameter Definitions

Run No.	Test Parameter				
	X1	X2	X3	X4	X4
1	1	1	1	1	1
2	-1	1	1	1	-1
3	-1	-1	1	1	-1
4	1	1	-1	1	-1
5	1	1	1	-1	-1
6	-1	-1	1	1	1
7	-1	1	-1	1	1
8	-1	1	1	-1	1
9	1	-1	-1	1	1
10	1	-1	1	-1	1
11	1	1	-1	-1	1
12	-1	-1	-1	1	-1
13	1	-1	-1	-1	-1
14	-1	1	-1	-1	-1
15	-1	-1	1	-1	-1
16	-1	-1	-1	-1	1

Table 13: Exposure Environments of Preliminary Test

Suitable adjustment of the pH with sodium hydroxide or hydrochloric acid was made. In the case of a wet/dry cycle the specimens were removed from the solution once each 24 hour cycle and placed in an oven at 80°C to dry for 5 to 6 hours.

A 1 litre beaker held 6 cylindrical specimens (25 mm ϕ x 50 mm). The 6 specimens included two of each of the three concrete mixes. The composition of the mixes, designated A, C, and CX, are given in Table 1 of Appendix II.

The two response variables which were used to monitor the condition of the specimens after exposure were weight change and visual inspection. The weight of each specimen was recorded at the onset of the experiment and then periodically during the course of the experiment. To obtain weight readings during the experiment each of the specimens was washed with warm water to remove any loose surface material and then allowed to air dry overnight before weighing. Each specimen was visually inspected and rated on its resistance to deterioration from 1 (best performance) to 4 (worst performance).

The original weight of the specimens was taken at the beginning of the experiment on May 18, 1983. Subsequent weight measurements were taken on May 27 (after 7 cycles) and on June 6 (after 13 cycles). Visual inspection was made on May 27 for mix CX and on June 6 for all three mixes.

4.2.4. Results and Discussion

The weights and weight changes of the specimens over the duration of the experimental work are summarized in Table 14. It is observed from this Table that the specimens gained weight between May 18

<u>Mix</u>	<u>Av. wt. of specimens, g</u> <u>May 18</u>	<u>Std. dev.</u>	<u>Av. wt. of specimens, g</u> <u>May 27</u>	<u>Std. , dev.</u>	<u>Av. wt. change</u> <u>g</u>	<u>Av. wt. of specimens, g</u> <u>June 6</u>	<u>Std. dev.</u>	<u>Av. wt. change</u> <u>g</u>
A	58.269	1.04	59.911	1.09	+1.64	59.618	1.08	-0.29
C	56.471	1.13	58.936	1.30	+2.47	58.380	1.21	-0.56
CX	54.596	1.04	57.514	1.11	+2.92	56.782	1.18	-0.73

Table 14: Average Weight of Specimens

and May 27 but subsequently lost weight between May 27 and June 6. The weight gains and subsequent weight losses are highest for CX specimens and lowest for Mix A specimens. Furthermore C and CX specimens showed the largest standard deviations. During the initial period the mass uptake of solution is greater than the loss of material due to chemical attack resulting in weight gain. In the second period, however, the loss of material is predominant and a net weight loss is observed.

The weight changes and visual assessment for individual specimens over the period May 27 to June 6 are summarized in Tables 1 and 2 of Appendix III respectively. The observations recorded are broadly in agreement as might be expected. Thus, those specimens which show the largest weight losses generally have the highest deterioration number and vice versa.

The $\hat{X}$ matrix is composed of the five exposure parameters outlined previously as well as all two-variable interactions between these five parameters. These are listed as Test Parameters in Table 15 which also includes the estimated parameters (beta values) as determined by least squares fit. In this way each column represents a mathematical model describing a particular set of the response variable (normalized weight loss or visual inspection number).

Since the beta values have been normalized it is not only possible to compare the relative importance of a particular variable within a given model (column-wise), but also possible to compare the relative importance between different models (row-wise). (Absolute values less than 0.10 have been omitted from the table for clarity.) If for the moment, only columns 1, 2, 4, 5, 6 and 7 are considered (columns

3 and 8 neglected) it is evident that certain parameters are causing most of the deterioration. Thus, from Table 15 it is evident that there are 4 important test parameters which significantly accelerate the deterioration process. The order of importance of these parameters are:

- i. Wet/dry cycling
- ii. Increased salt concentration
- iii. Wet/dry cycling and increased salt concentration
- iv. Increased immersion temperature

The above is statistically true only insofar as consistent data are obtained if the third and eighth columns of Table 15 can be neglected. The justification for doing so is that column eight is the result of a mathematical model using weight loss measurements on specimens of mix A as the response variable. Since mix A was the high quality mix it showed better resistance to deterioration than the other two mixes. This resulted in less material being leached away from each specimen and as a consequence the observed weight loss was not large enough to overcome the natural scatter expected in this type of experiment. This is clearly shown in Table 14 where the magnitude of the weight change measurements are much smaller for mix A than for either mix C or CX. Thus a model fitted to these data would not be expected to yield significant results.

The third column is a result of using weight loss measurements with mix CX as the response variable. The fourth column is generated using identical data to that of column 3 with the exception that 2 of the 32 measurements have been corrected. The need to correct these two measurements stems from the observation that the weight loss

Table 15: Normalized Beta Values

COLUMN	NORMALIZED BETA VALUES ^{1,2,3}									
	Test Parameter	VI ⁴ ; MixCX May 27	VI; MixCX June 6	Wt ⁵ ; MixCX June 6	Correct Wt; MixC*June 6	VI; MixC June 6	Wt; MixC June 6	VI; MixA June 6	Wt; MixA June 6	
1.	Intercept	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
2.	Immersion Temp.	.10	-	-	.13	-	.12	-	-.17	
3.	Wet/Dry Cycling	.24	.47	.33	.39	.35	.45	.28	1.22	
4.	Partial Immersion	-	-	-	-	-	-	-	-3.1	
5.	Increased Salt Conc.	.31	.24	.25	.32	.35	.28	.41	-	
6.	pH	-	-	.11	-	-	.14	-	.33	
7.	Temp. & Wet/Dry	-	-	-.11	-	-	-	-	-	
8.	Temp. & Partial Immersion	-	-	.12	-	-	-	-	-9.5	
9.	Temp. & Increased Salt Conc.	-	-	-.17	-	-	-	-	-1.03	
10.	Temp. & pH	-	-	.16	-	-	-	-.15	1.08	
11.	Wet/Dry & Partial Immersion	-	-	.15	-	-	-	-	.75	
12.	Wet/Dry & Increased Salt Conc.	.10	.18	.33	.39	.18	.14	.21	.48	
13.	Wet/Dry & pH	-	-	-	-	-	-.17	-	-1.09	
14.	Partial Immersion & Increased Salt Conc.	-	-	.14	-	-	-	-	-	
15.	Partial Immersion & pH	-.10	-	-.16	-	-	-	-	.28	
16.	Increased Salt Conc. & pH	-	-	.13	-	-	-.31	-	-	

1. Normalized beta values are defined as actual beta value divided by actual beta intercept.
2. Beta values of absolute value less than 0.10 are omitted for clarity.
3. Positive beta values are indicative of detrimental effects to concrete while negative beta values are indicative of beneficial effect to concrete.
4. VI - visual inspection
5. Wt. - implies weight change between May 27 and June 6.

measurements and the visual inspection are not consistent. Of the four sets of two specimens that exhibit severe deterioration, specimens CX41 and CX42 appear to have significantly smaller initial weight gain measurements, see Table 3 of Appendix III. If it is assumed that all specimens that show severe deterioration should show the same initial weight gain or at least be distributed about a mean value, then the 95% confidence interval for the initial normalized weight gain is given by:

$$0.0609 \pm 2.57 (0.075/ 5)$$

or

$$0.0523 \text{ to } 0.0695$$

As can be seen from Table 3 of Appendix III the initial gains for specimens CX41 and CX42 do not fall within this interval. The initial weight gain of CX41 and CX42 is corrected by assuming that these specimens should show the initial weight gain equivalent to the average of the other six specimens which exhibit severe deterioration. When this is done it results in a higher initial weight gain and a larger subsequent weight loss. Column 4 of Table 14 is the result of using these corrected weight measurements and column 4 does indeed show consistent results with the other data.

The probable explanation is that the erroneous weight measurements of specimens CX41 and CX42 were caused by the overlapping of two trends. That is, the weight gain by salt absorption was masked by weight loss due to deterioration of the concrete.

4.2.5 Preliminary Conclusions

The preliminary experiment showed that of the five chosen environmental parameters (increased immersion temperature, wet/dry

cycling, partial immersion, increased salt concentration and decreased pH), the parameters and combinations of parameters that contribute significantly to the process of deterioration of concrete are, in order of importance:

- i. Wet/dry cycling
- ii. Increased salt concentration
- iii. Wet/dry cycling and increased salt concentration
- iv. Increased immersion temperature.

From this preliminary test it was decided to incorporate two of the four important parameters. An accelerated testing sequence was then designed which incorporated both the wet/dry cycle and the increased immersion temperature. The use of increased salt concentration was not incorporated since it was felt that this would deviate greatly from the actual working environment thereby causing the results of the investigation to be questioned.

4.3 APPARATUS DESIGN

The accelerated test apparatus was designed to meet the criteria developed in the preliminary experiment. The parameters which were included were increased immersion temperature and wet/dry cycling. The test was also designed to accommodate large concrete specimens as opposed to small mortar specimens. Additional specimens were required as a control for evaluation of results.

Figures 10a and 10b indicate the overall set up of the apparatus. Two sets of specimens were used for testing; 152 mm ϕ x 305 mm cylinders and 76 mm x 101 mm x 406 mm prisms. Identical fiberglass lined plywood boxes were constructed, each with a separate fiberglass

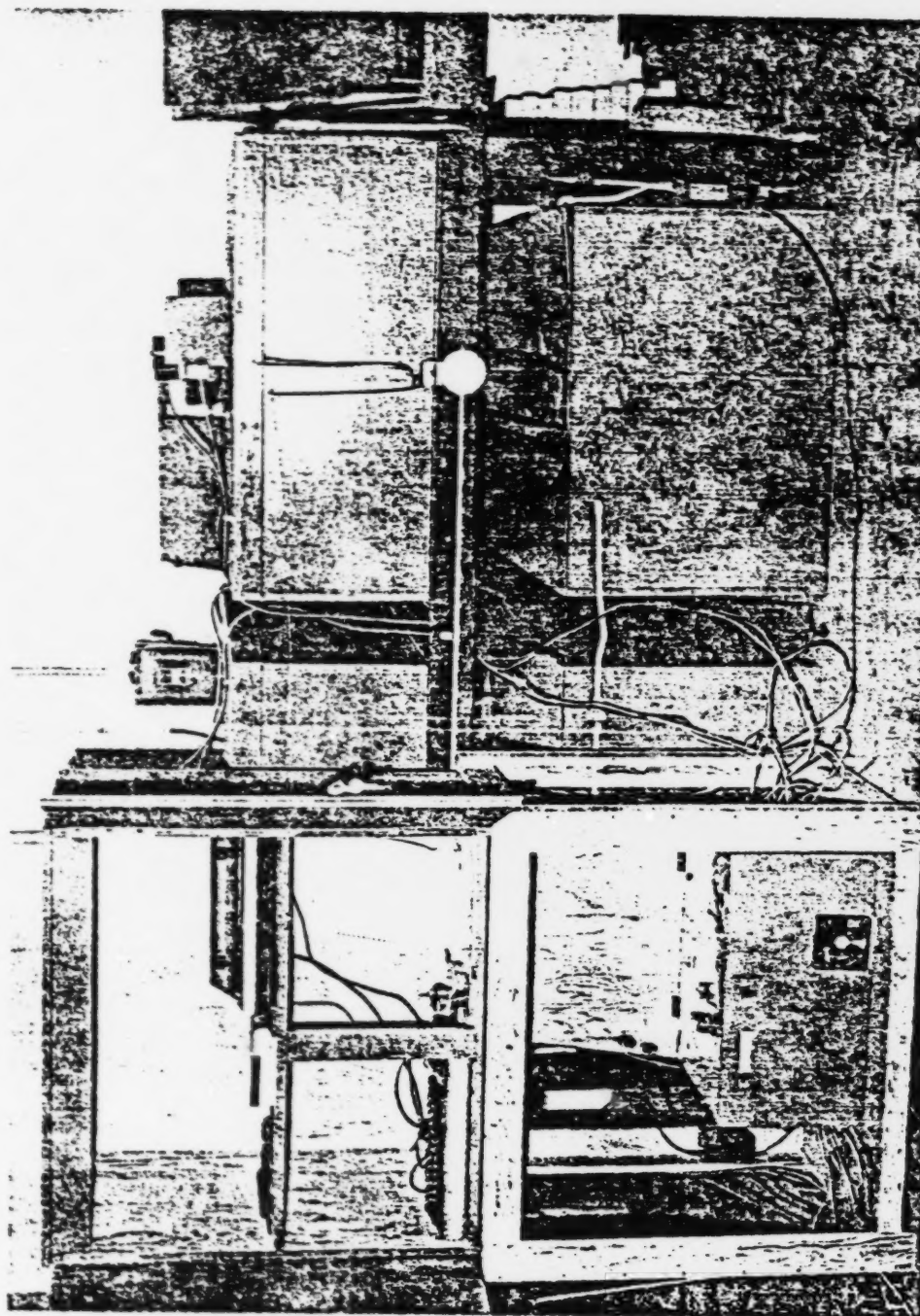


Figure 10a: General View of Accelerated Testing Apparatus
- Overall

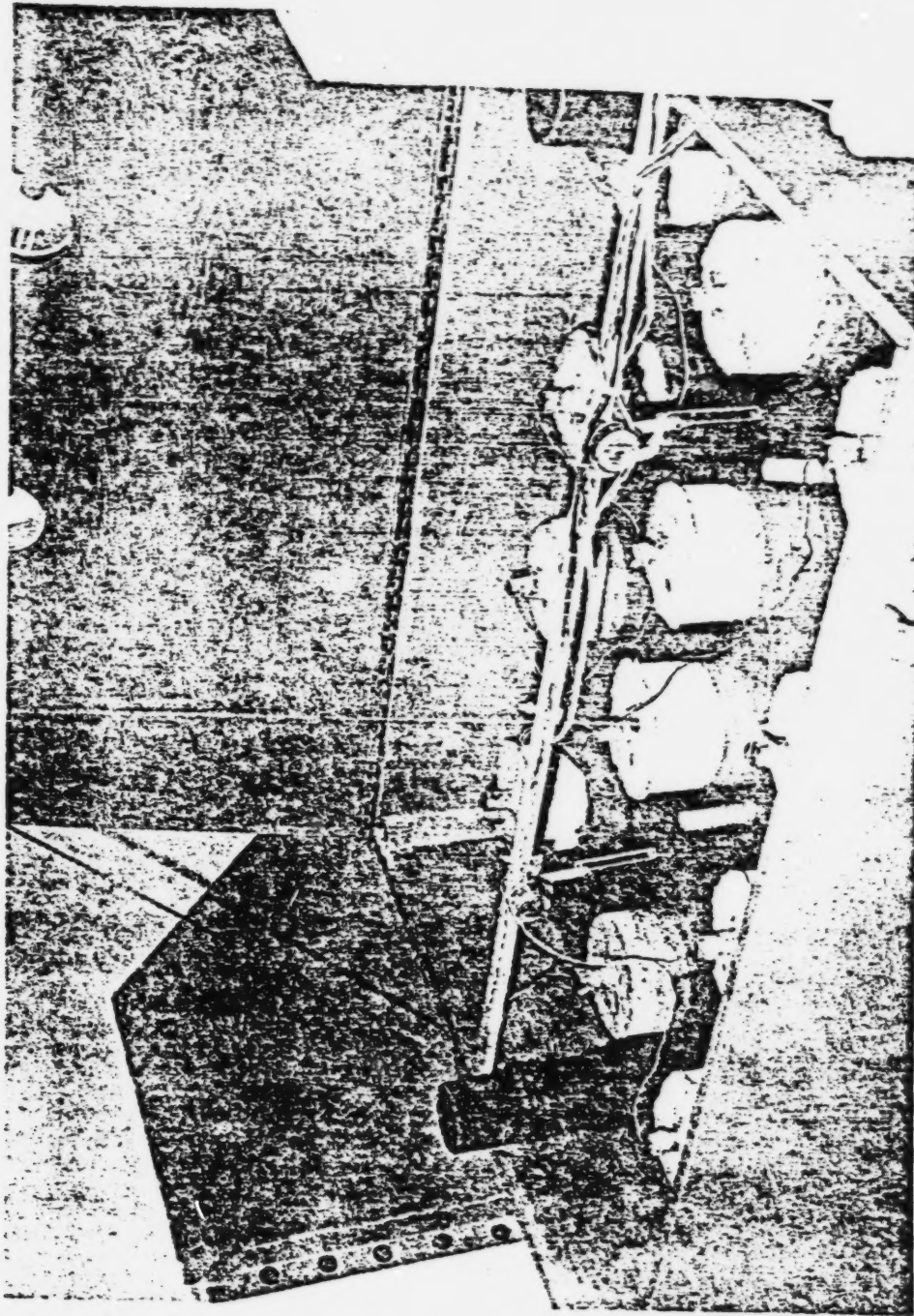


Figure 10b: General View of Accelerated Testing Apparatus
- Specimens

lined plywood box reservoir. The tanks were large enough to hold 3 rows of 4 cylindrical specimens with 150 mm clear around each specimen.

The air was heated by two, 1500 watt electrical heaters mounted on the hinged plywood top of each tank. A fan and PVC ductwork dispersed the hot air throughout the specimen box.

The saltwater solution was contained in the reservoir boxes which were located underneath each specimen tank. The salt solution was pumped from a reservoir to the specimen tank through plastic piping. The water level in the specimen tank was controlled by two flush valves each with a water overflow tube. The flush valves were activated by a 1 rpm humidifier motor. The flush valves drained into the reservoir tanks. Care was taken to ensure that no metal parts came into contact with the salt solution.

The specimen tanks measured 1.46 m x 1.00 m x 0.55 m high. The overflow tubes allowed for 20 cm of water in the specimen tanks. The reservoir tanks measured 1.37 m x 0.91 m x 0.64 m high and were filled with 653 liters of salt solution. One cycle contained the following steps;

- 1) Turn off the hot air blowers and turn the pumps on to fill the specimen tanks to the overflow level.
- 2) Leave the specimens in solution for the prescribed time of the wet cycle.
- 3) Engage the 2 rpm motors for 1/2 revolution--opening the flush valves--and draining the solution into the reservoir tank.
- 4) Turn on the hot air blowers and close the flush valves (when drained).
- 5) Leave the specimens for the prescribed time of the dry cycle.

The entire cycling process was controlled electrically by interfacing a small personal computer to the 1 rpm motor, blowers, and pumps. The computer was programmed to engage and subsequently disengage each of the electrical devices to produce the required cycles. In this manner automatic cycling 24 hours a day over extended time periods was possible.

4.4 CYCLE TIME AND TEMPERATURE

The hot air drying portion of the cycle was operated between 69°C and 75°C, while the wet portion of the cycle was operated at 30 to 34°C. No heat was applied to the salt solution, however, a slight rise from ambient temperature to 30-34°C occurred due to the residual heat retained by the specimens from the hot air portion of the cycle. The slight heating effect of the solution was quickly realized after a few cycles and remained constant throughout operation of the apparatus. While the immersion temperature was lower than that employed in the preliminary tests, it was high relative to seawater on Canada's coasts.

Cycling times were based on the measured thermal response of the cylindrical and prismatic specimens to the wet and dry portions of the cycle. The prismatic specimen A45 and the cylindrical specimen A38 were cast with Copper/Constantan thermocouples located at various positions throughout their mass. (Refer to Appendix II for detailed description and location of the thermocouples.) Figures 11a and 11b respectively show the thermal response of the prismatic and cylindrical specimens to the hot air drying cycle, while Figures 12a and 12b show the thermal response during the wet portion of the cycle. It was decided to allow the entire mass of the specimens to approach the operating temperature during each portion of the cycle. As a

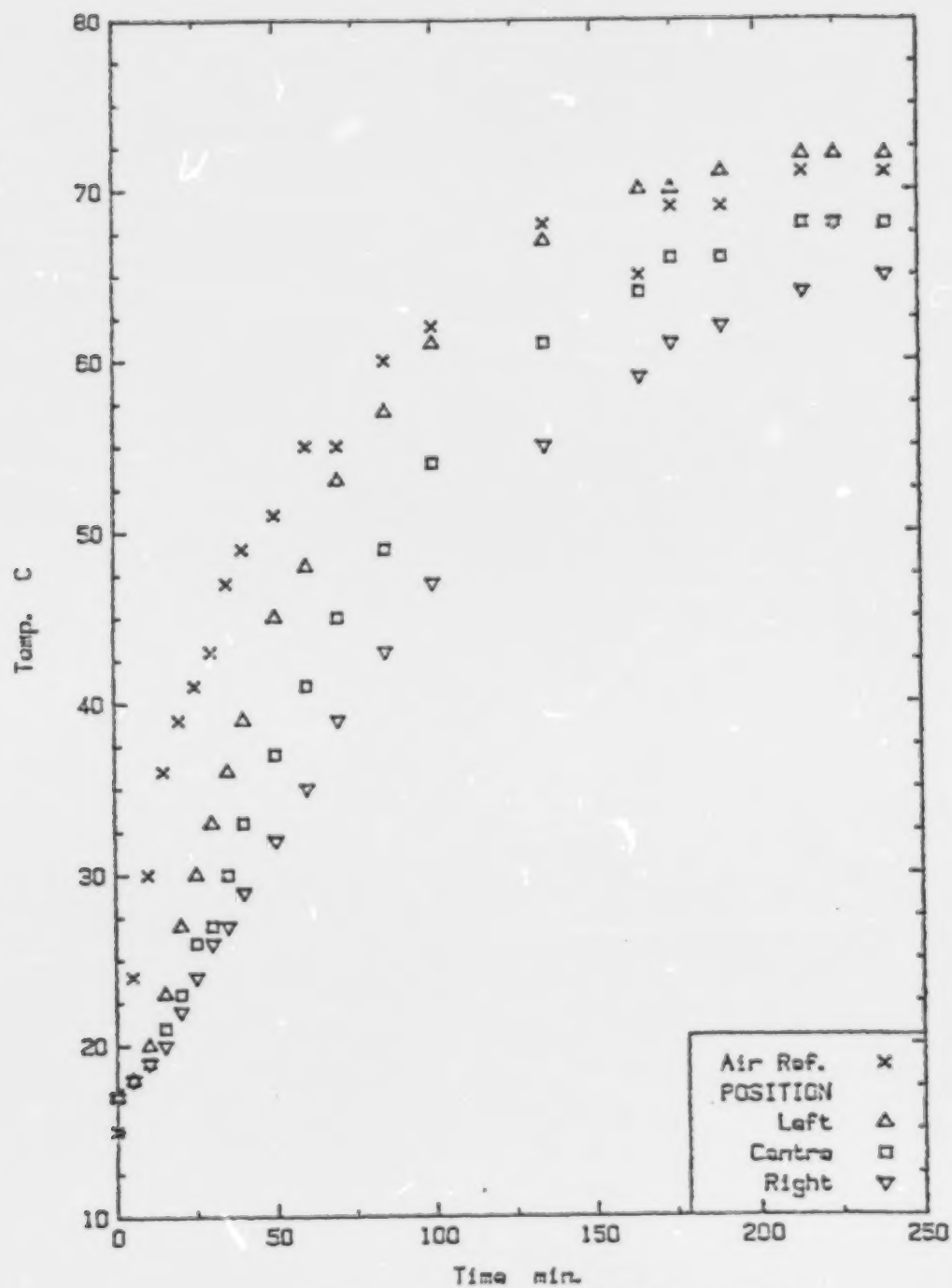


Figure 11a: THERMAL RESPONSE OF PRISMATIC SPECIMEN
TO HOT AIR DRYING
TEMPERATURE VS TIME

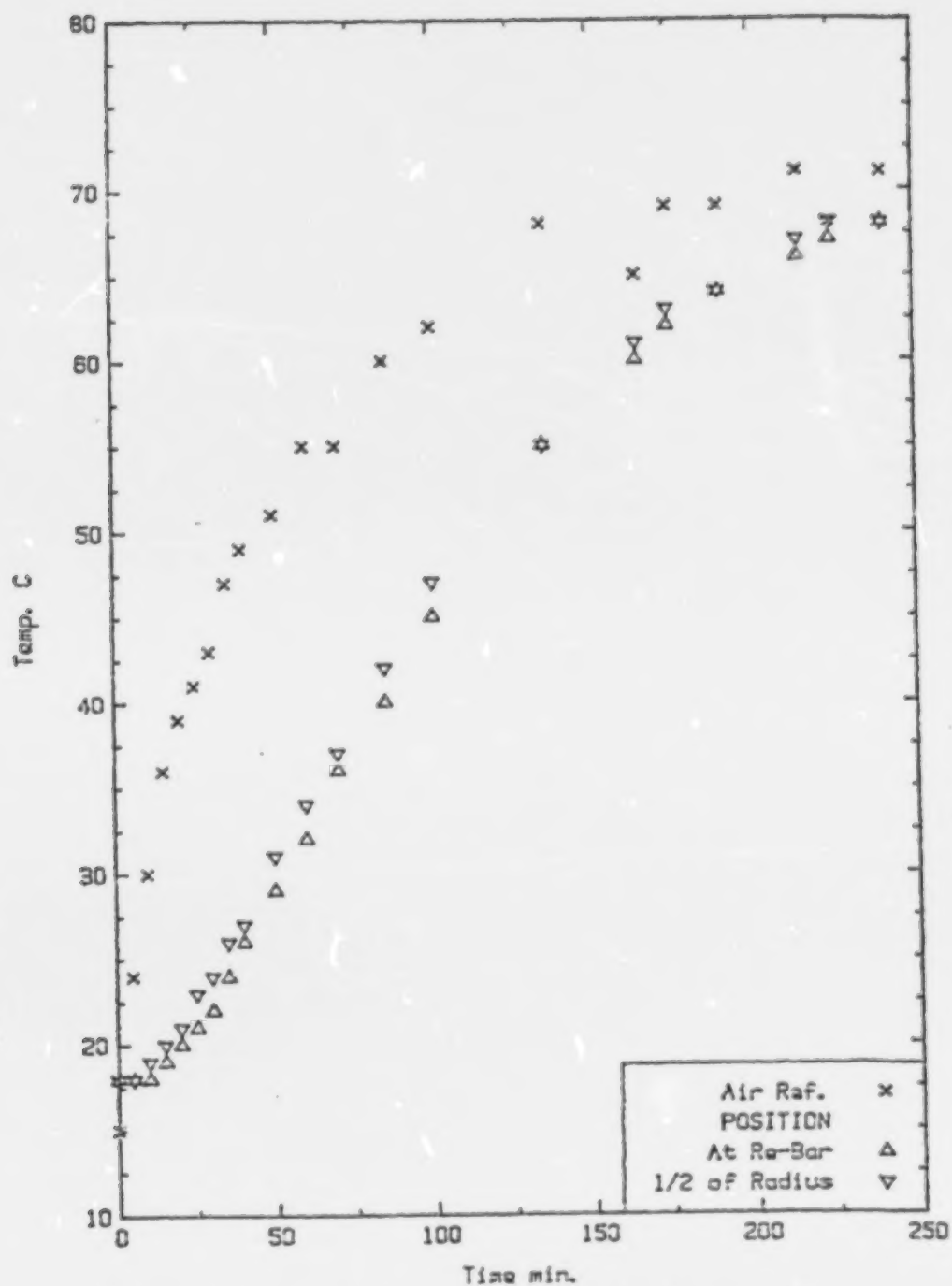


Figure 11b: THERMAL RESPONSE OF CYLINDRICAL SPECIMEN
TO HOT AIR DRYING
TEMPERATURE VS TIME

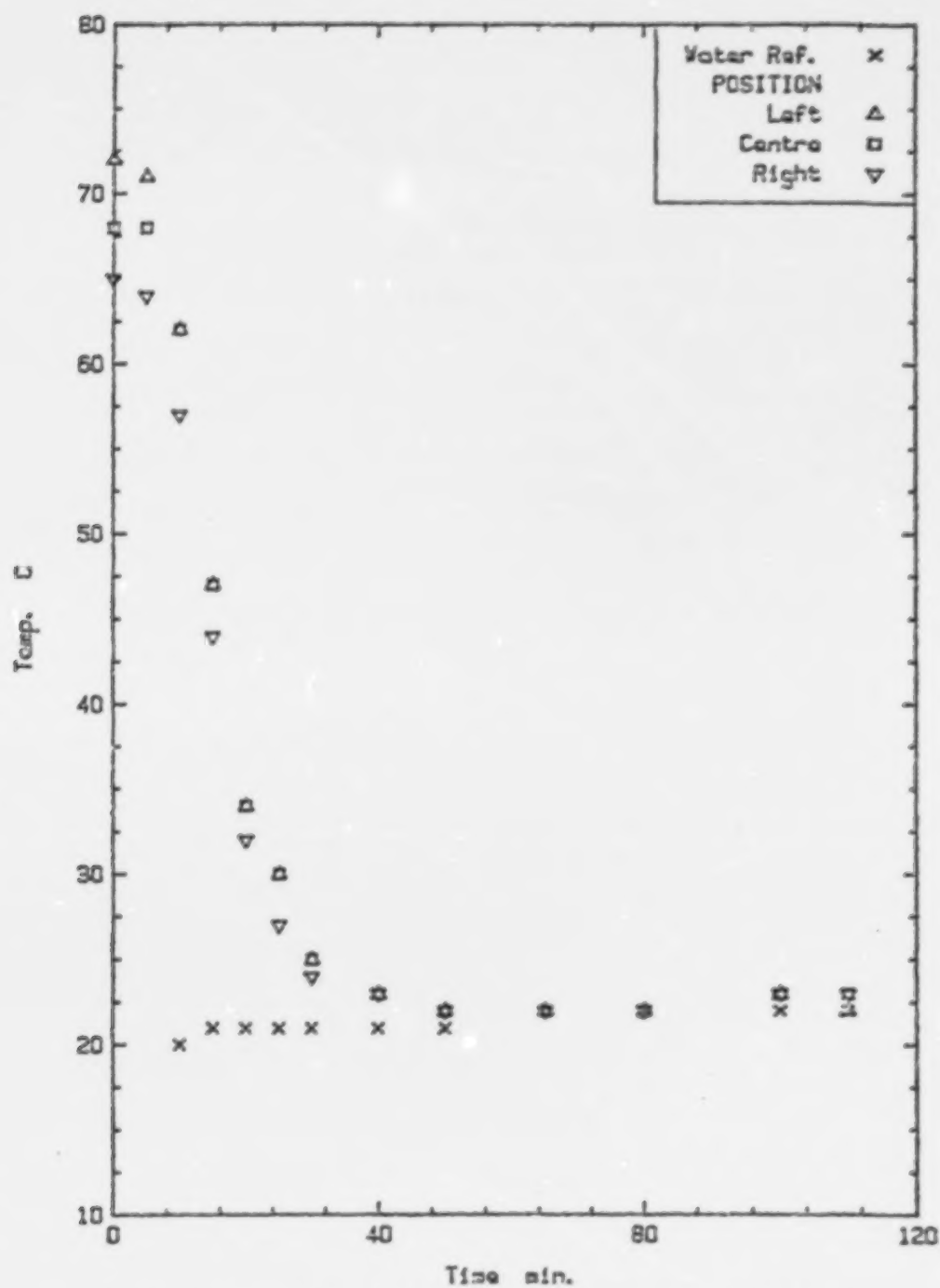


Figure 12a: THERMAL RESPONSE OF PRISMATIC SPECIMEN
TO WATER IMMERSION
TEMPERATURE VS TIME

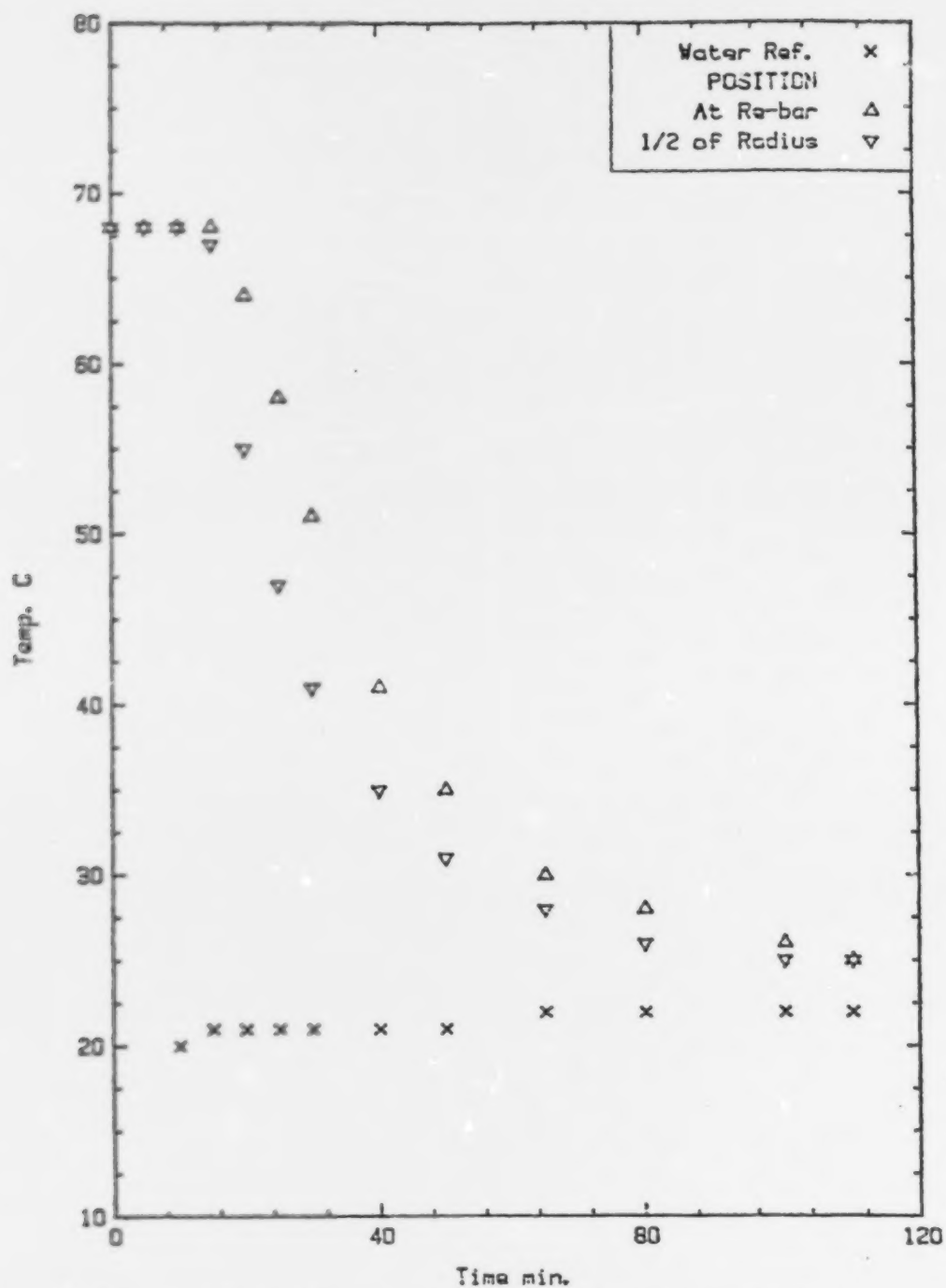


Figure 12b: THERMAL RESPONSE OF CYLINDRICAL SPECIMEN
TO WATER IMMERSION
TEMPERATURE VS TIME

consequence, a drying time of 4 hours and an immersion time of 2 hours were chosen. Heat transfer with water as the medium was superior to that of air as the medium; this is illustrated by the unequal times of the wet and dry portions of the cycle.

This total cycle time of 6 hours allowed for 4 complete cycles to be performed within a 24 hour period, versus 2 tidal cycles in the natural environment.

4.5 SPECIMEN LOCATION

Both the 152 mm ϕ x 305 mm cylindrical and the 76 mm x 101 mm x 406 mm prismatic specimens were evaluated for durability in the accelerated testing apparatus. The first specimen tank contained 4 cylindrical replicates of each of the three mixes outlined in Appendix II. These specimens were placed in an upright position with the steel reinforcement extending out of the top of the concrete. These specimens were only partially immersed during the wet portion of cycle with 105 mm of the specimens out of the solution). The second specimen tank contained the prismatic specimens, again with 4 replicates of each of the 3 mixes. These specimens were totally immersed during the wet portion of the cycle.

4.6 SPECIMEN MONITORING

In order to monitor the deterioration of the specimens, four different measurements were made at periodic intervals during the test.

The specimens were removed from the apparatus for a short period of time to take these measurements. This time was negligible compared to the overall duration of the test. The following measurements were made:

- 1) The weight of the specimen in air
- 2) The weight of the specimen under water
- 3) The transit time of a sound pulse through the specimen
- 4) The resonant frequency of prisms only.

In addition to this, the corrosion potential (relative to a saturated calomel electrode) of the steel reinforcement bar in the cylindrical specimens was measured.

Measurement of the weight in air and the weight under water were used to calculate the volume and density of the specimens. The observed weight difference between the specimens in air and under water is equivalent in magnitude to the buoyancy force exerted by the water on the specimen. Further, the buoyancy force is equivalent to the weight of water displaced.

Thus

$$V \rho_w = W_A - W_w$$

where:

V = the volume of the specimen

ρ_w = the density of water

W_A = the observed weight of the specimen in air

W_w = the observed weight of the specimen under water.

The density of the specimen is defined as mass per unit volume.

Thus

$$\rho = \frac{W_A}{V}$$

or

$$= \frac{W_A \rho_w}{(W_A - W_w)}$$

where

ρ = the density of the concrete specimen.

The transit time of a sound pulse through a specimen can be used as a relative indicator of the dynamic modulus of elasticity. The relationship between the velocity of a sound pulse (reciprocal of transit time per unit length) is given by Bungey⁵¹ as:

$$V = \sqrt{\frac{K \cdot E_d}{\rho}}$$

where:

v = the velocity,

E_d = the dynamic modulus of elasticity, and

$$K = \frac{1 - \nu}{(1 + \nu)(1 - 2\nu)}$$

ν = the dynamic Poisson ratio.

Bungey states that value of K is relatively insensitive to variation in ν , thus K can be considered constant. Since all prisms and cylinders had identical path lengths, the transit time of a sound pulse can be used directly as a comparison between specimens by realizing that:

$$E_d = \frac{v^2 \rho}{K}$$

and that

$$v = L/t$$

where:

L = the path length, and

t = the transit time of the sound pulse.

Thus for specimens of equivalent path length,

$$E_d \propto \frac{1}{t^2}$$

The transit time of a sound pulse through the specimen is increased by factors such as microcracking, bond weakening (between the aggregate and paste), and other factors which disrupt the continuity of the concrete.

The resonant frequency of a prism can also be related to the dynamic modulus of elasticity:

$$E_d = C W_A n^2$$

where:

E_d = the dynamic modulus of elasticity in N/m^2 ,

W_A = the mass of the specimen in kg,

n^2 = the fundamental transverse frequency in Hz,

$C = 0.944L^3 T/ba^3$, in which

L = the specimen length in m,

b and a are the dimensions of the cross section in m,

a = the direction which the prism is being resonated, and

T = a correction factor.

The above is adapted from ASTM C215-60, which also tabulates values for T . Thus, for equivalent sized specimens:

$$E_d \propto W_A n^2$$

The two methods of calculating E_d are comparable, but not entirely consistent as Table 16 indicates. Uncertainties in the K and T values as well as inherent errors in the procedures are the probable explanations for the discrepancies. As a consequence the relative changes as a function of ρ/t^2 for the transit time measurements and $W_A n^2$ for the resonant frequency measurements were monitored in this study.

The condition of the steel reinforcement embedded in the concrete specimens was monitored periodically by measuring the corrosion potential. This was accomplished by connecting one side of a high impedance voltmeter to the steel bar and the other side to a saturated

SPECIMEN	DYNAMIC MODULUS OF ELASTICITY, N/m^2	
	by TRANSIT TIME	by RESONANT FREQUENCY
A43	4.50×10^{10}	3.61×10^{10}
C43	4.22×10^{10}	3.45×10^{10}
CX43	4.09×10^{10}	3.43×10^{10}

Table 16: Dynamic Modulus of Elasticity from Transit
Time and Resonant Frequency Measurements

calomel electrode (SCE). Thus the measurement of the corrosion potential was made in reference to the SCE. These measurements were taken just before the end of the wet portion of the cycle in order that the salt solution would act as the electrolyte between the steel reinforcement and the SCE.

4.7 SALT SOLUTION

Seawater contains three different ions which can affect the durability of steel reinforced concrete (Mg^{+2} , $SO_4^{=}$ and Cl^{-}). The first two species chemically attack the hardened cement paste while the latter can induce corrosion of the steel reinforcement. From ASTM designation D1141-75, which describes the preparation of substitute seawater, the concentrations of these three principal ions can be calculated. The result of such a calculation is presented in the first column of Table 17.

ION SPECIES	CONCENTRATION, mg/l	
	FROM ASTM D1141-75	ACTUAL ADDITION
Cl^-	19,500	17,500
Mg^{+2}	1,329	1,020
SO_4^-	6,734	4,020

Table 17: Principal Ion Concentration from ASTM
Designation D1141-75 and Actual Addition

The ASTM designation on the preparation of substitute seawater requires that both distilled water and high purity grade salts be used. The ASTM designation also requires addition of other ions in lesser quantities. This procedure was not entirely satisfactory owing to the large volume of solution which would be required during the course of the experiment. Instead tap water, standard grade sodium chloride, and technical grade magnesium sulphate septahydrate were used to prepare the salt solution. The advantage of this was that the volume of solution required with principal ions needed could be prepared at a substantially lower cost. The concentrations of Mg^{+2} , SO_4^- and Cl^- introduced in this manner are presented in the second column of Table 17.

Six hundred and fifty-three liters of salt solution were made up for each reservoir. This provided a mass ratio of water to concrete of 4.3 and 7.8 for the cylindrical and prismatic specimens respectively. The salt solution was changed once during the course of the experiment after 227 cycles. Water lost through evaporation was replenished as

required. Measurements on the rate of evaporation showed that approximately 2 liters of water were lost per tank per cycle when the system was operating at a steady state of 4 cycles per day.

The concentration of Ca^{+2} , Mg^{+2} , Cl^- , and SO_4^- were determined by chemical analysis on the salt solutions in both reservoirs just before the solutions were changed and on the newly made up replacement solution. The results of these measurements are presented in Table 18. Variations in the ion concentration are detected between the solution after it is made up and after it was circulated in the apparatus. The measured ion concentrations compare favourably with the calculated target values (refer to the second column of Table 17).

ION	CONCENTRATION, mg/liter		
	TANK #1*	TANK #2*	REPLACEMENT SOLUTION
Cl	18219	18681	17500
Mg	1015	1039	1040
SO_4	4148	4385	4470
Ca	50.7	61.9	42.1

Table 18: Ion Concentrations Measured in the Salt Solutions

*Corrected for Water Evaporation

CHAPTER 5

5.0 RESULTS AND DISCUSSION

5.1 BACKGROUND

The apparatus was designed to operate at 4 cycles per day, however, due to technical problems in interfacing the computer with the apparatus this was not always possible. When difficulties arose the system was operated manually at a reduced number of cycles per day. The length of the wet and dry portions of the cycle remained unchanged during this time. The result was that there were times when the apparatus was not in operation; at these times the specimens were allowed to remain in the salt solution. Figure 13 is a histogram summarizing the number of cycles per day during the course of the experiment.

The specimens were subjected to a total of 975 cycles over a 5 month period. Measurements on the specimens were made at the onset of the experiment and at 27(28), 53(54), 119(120), 204(203), 265(265), 335(335), 427(427), 550, 658, 734, 828, 975 cycles. Bracketed numbers refer to the cylindrical specimens if different than prismatic specimens. Weight in air, weight under water, transit time of a sound pulse through the specimen, and resonant frequency (prisms only) were measured. From these measurements, the volume and density for each specimen were calculated. In addition, the quotient of the density by the square of the transit time (ρ/t^2) and the product of the weight in air and the square of the resonant frequency ($W_A n^2$) were calculated. Both of these latter calculations were used to indicate relative changes in the dynamic modulus of elasticity (refer to section 4.6).

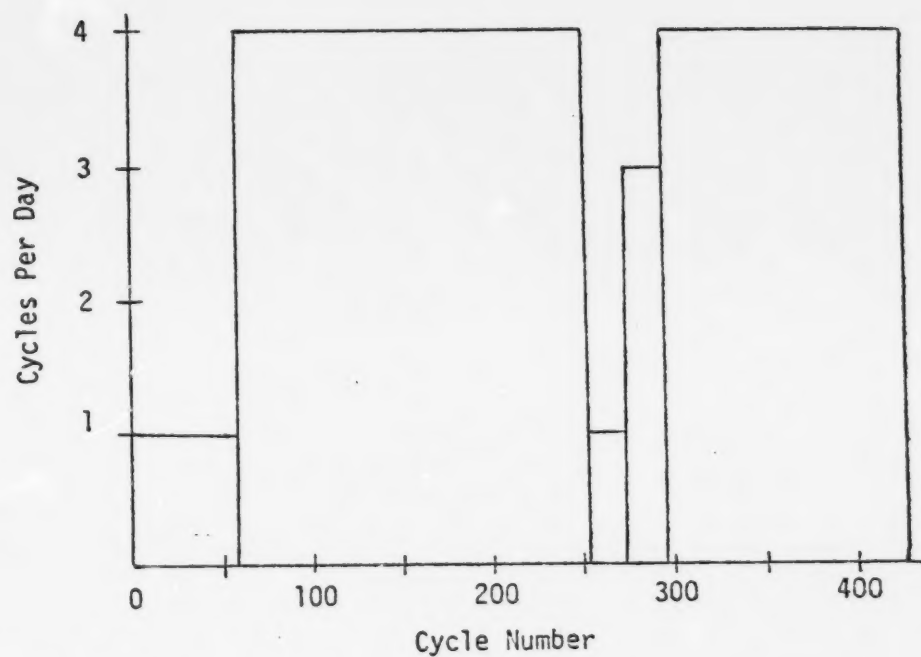


Figure 13: No. of Cycles per Day for the Apparatus over the course of the Accelerated Durability Test

In addition to the test specimens, control specimens were monitored. The control specimens were identical to the test specimens except that they did not undergo wet-dry cycling. The control specimens were kept in a moist cure room at a constant room temperature over the period of the test. Three prismatic specimens and two cylindrical specimens per mix were used as controls; four prismatic and four cylindrical specimens per mix were used for testing.

Identical measurements to those performed on the test specimens were performed on the controls. Measurements on the controls were made at the same time as measurements on the test specimens.

5.2 MEASUREMENTS

5.2.1 Physical Measurements

Tabulated results of the physical measurements are presented in Appendix IV. Figures 14a through 17b present the changes (expressed as a percentage of the original value) in these physical properties for the three mixes verses the number of cycles. Test and control results are plotted for each mix. These figures respectively refer to weight in air, weight under water, density and volume. Figure numbers followed by "a" refer to prismatic specimens and those followed by "b" refer to cylindrical specimens. The results of transit time measurements, expressed as ρ/t^2 , and of resonant frequency measurements, expressed as $W_A n^2$, are presented in Figures 18a, 18b, and 19 (resonant frequency could only be measured for the prismatic specimens).

Each point on the aforementioned plots for the test specimens is a result of an average of 4 test specimen replicates.

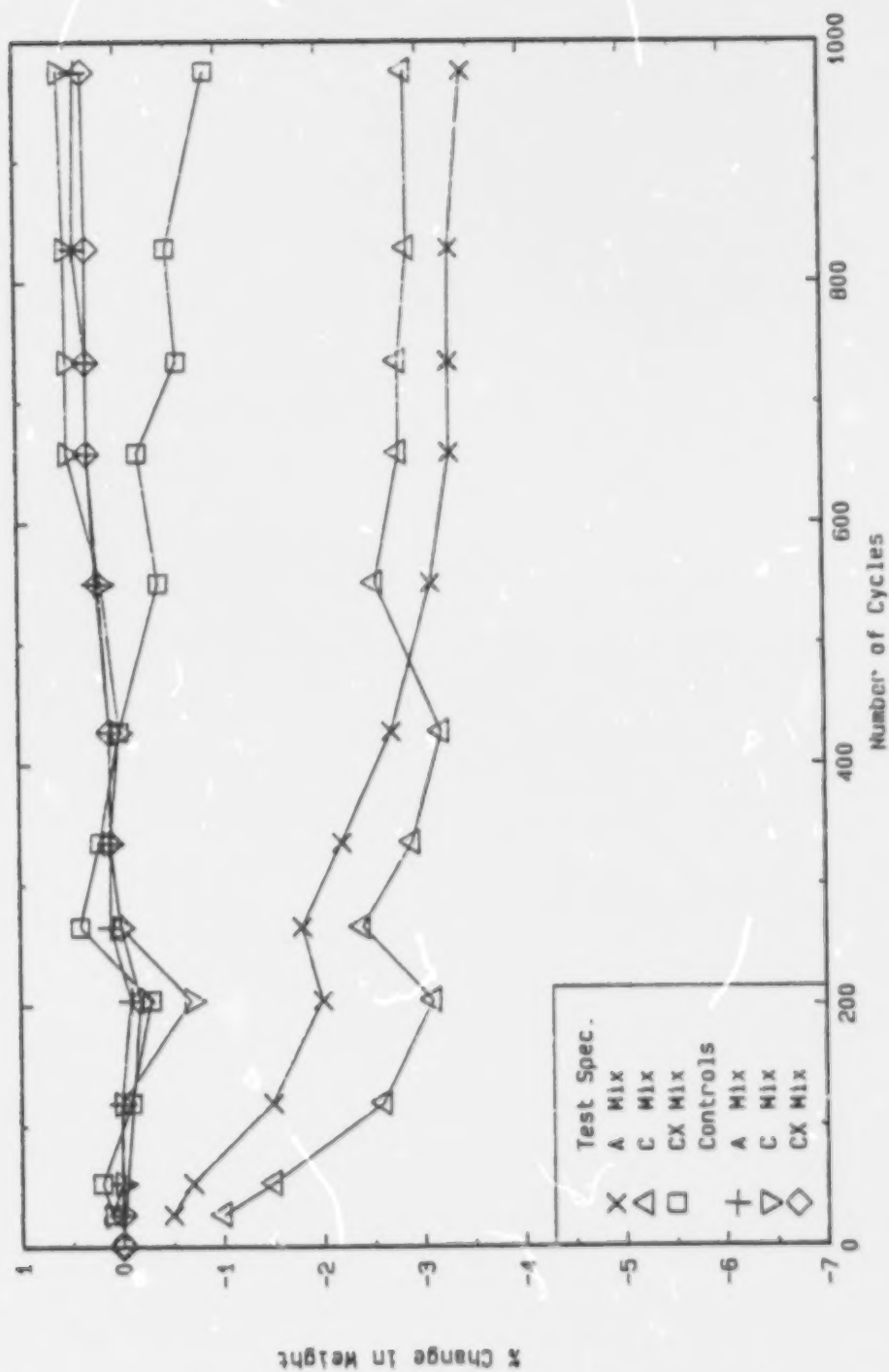


Figure 14e: Percent Change in Weight vs Number of Cycles
Prismatic Specimens

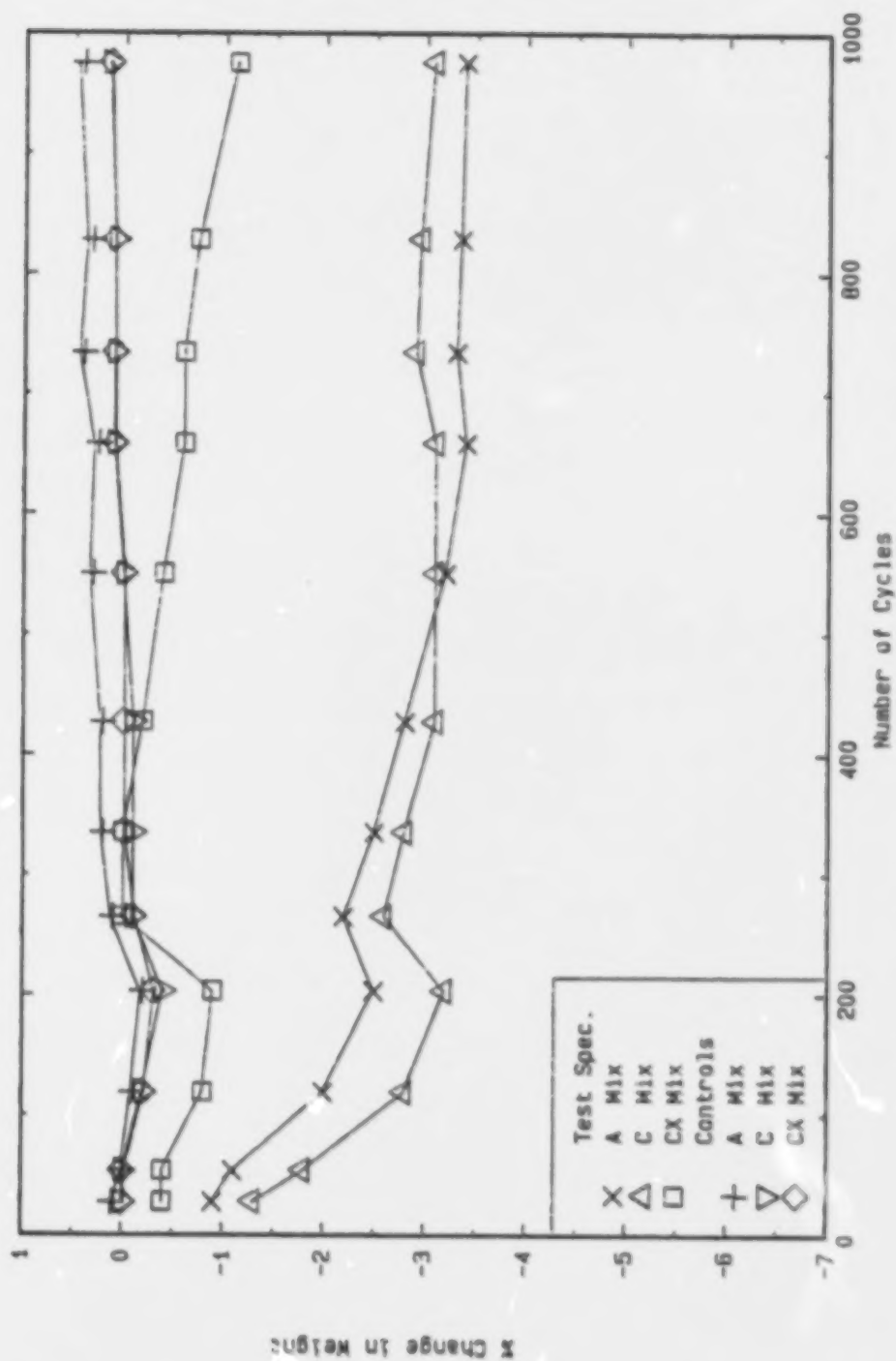


Figure 14b: Percent Change in Weight vs Number of Cycles
Cylindrical Specimens

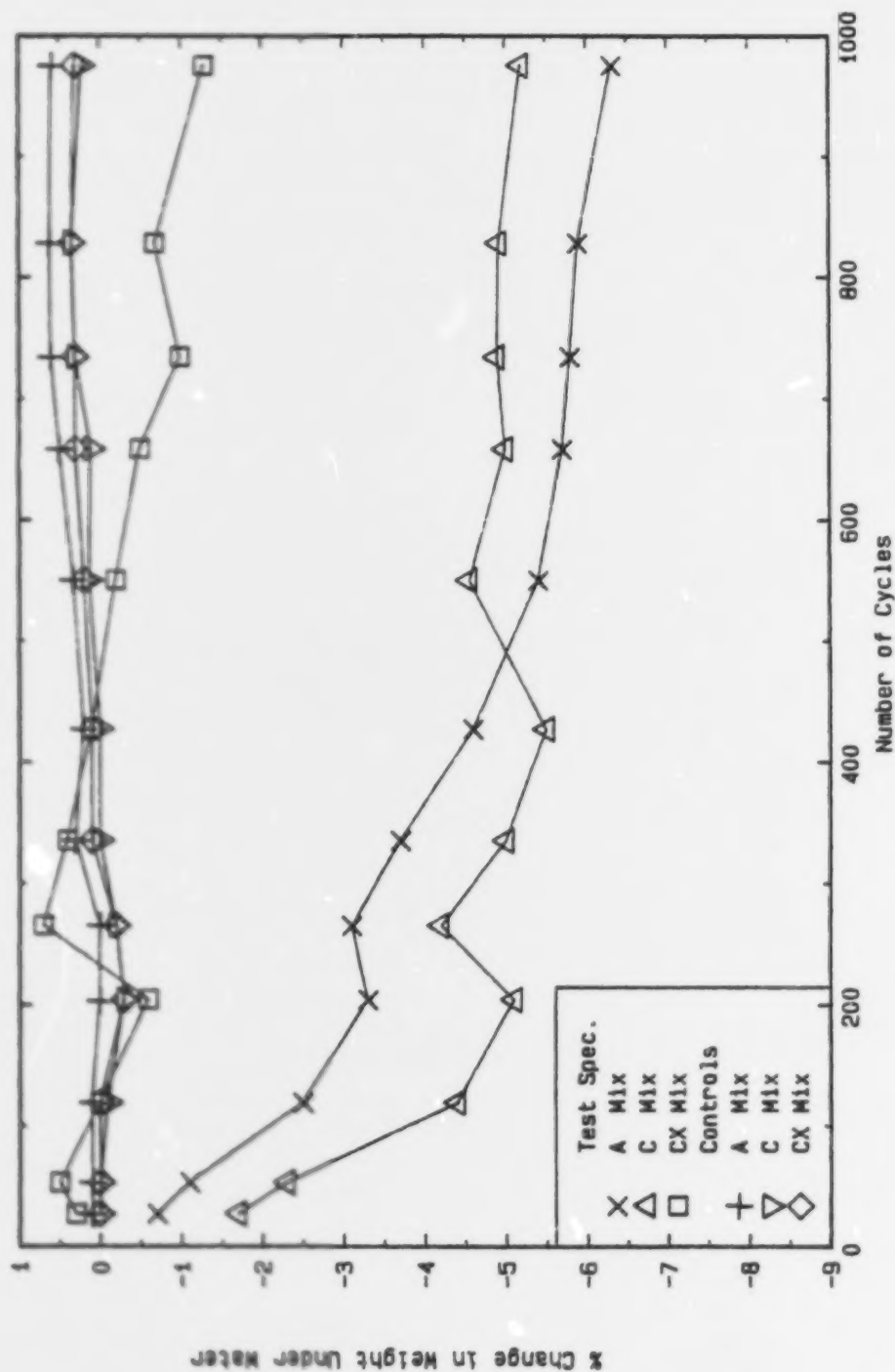


Figure 15a: Percent Change in Weight Under Water vs Number of Cycles
Prismatic Specimens

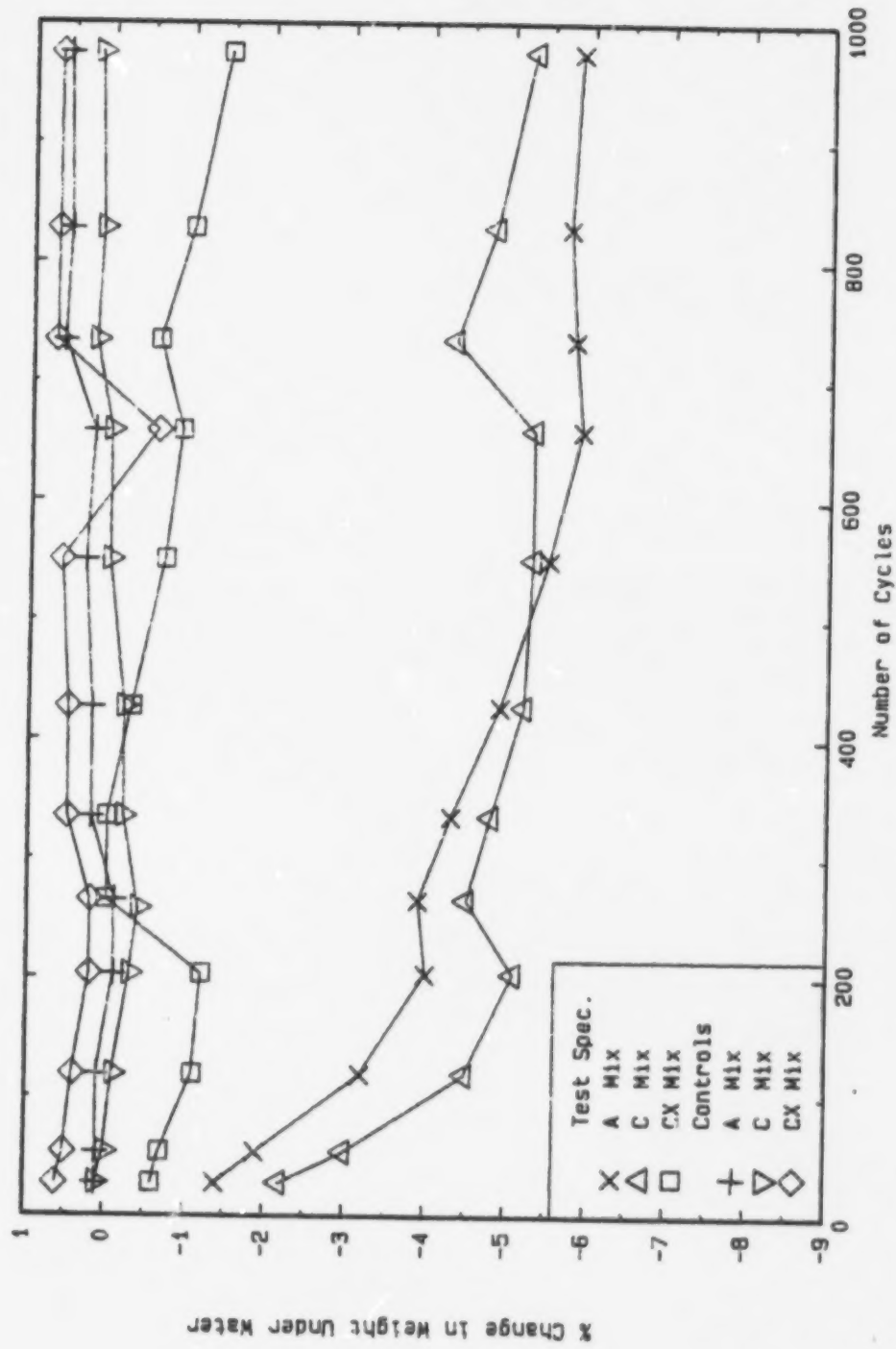


Figure 15b: Percent Change in Weight Under Water vs Number of Cycles
Cylindrical Specimens

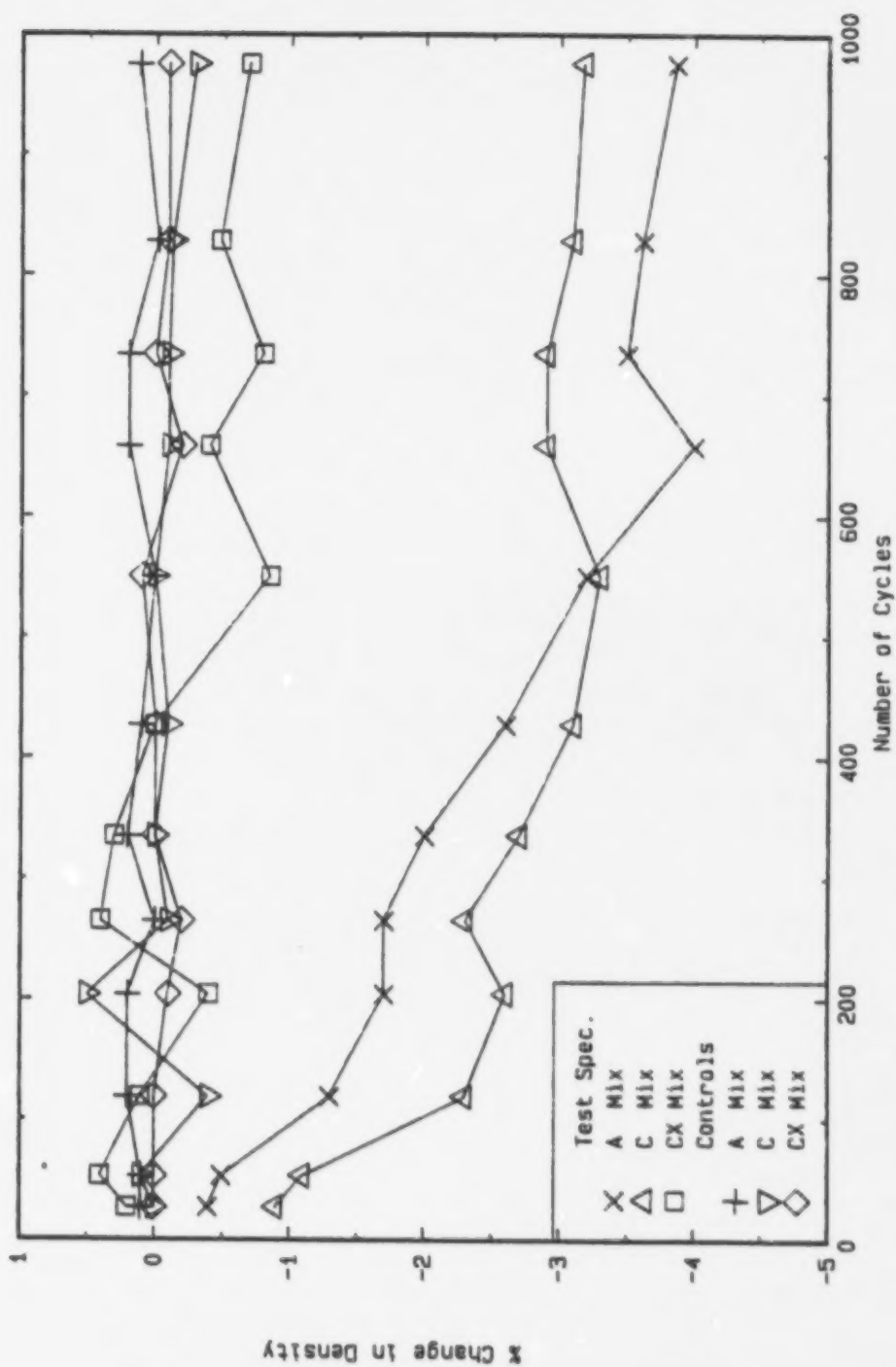


Figure 16a: Percent Change in Density vs Number of Cycles
Prismatic Specimens

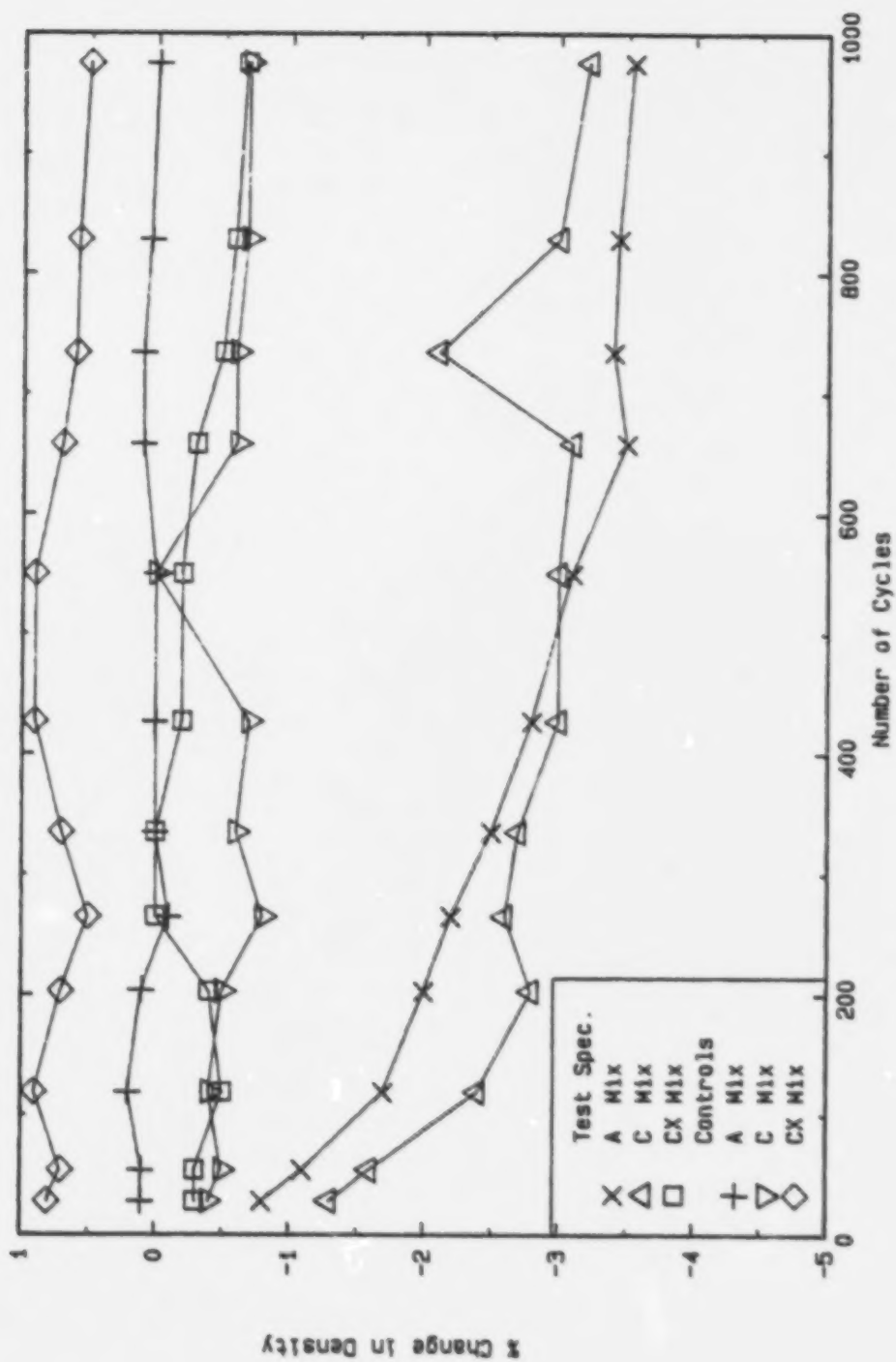


Figure 16b: Percent Change in Density vs Number of Cycles
Cylindrical Specimens

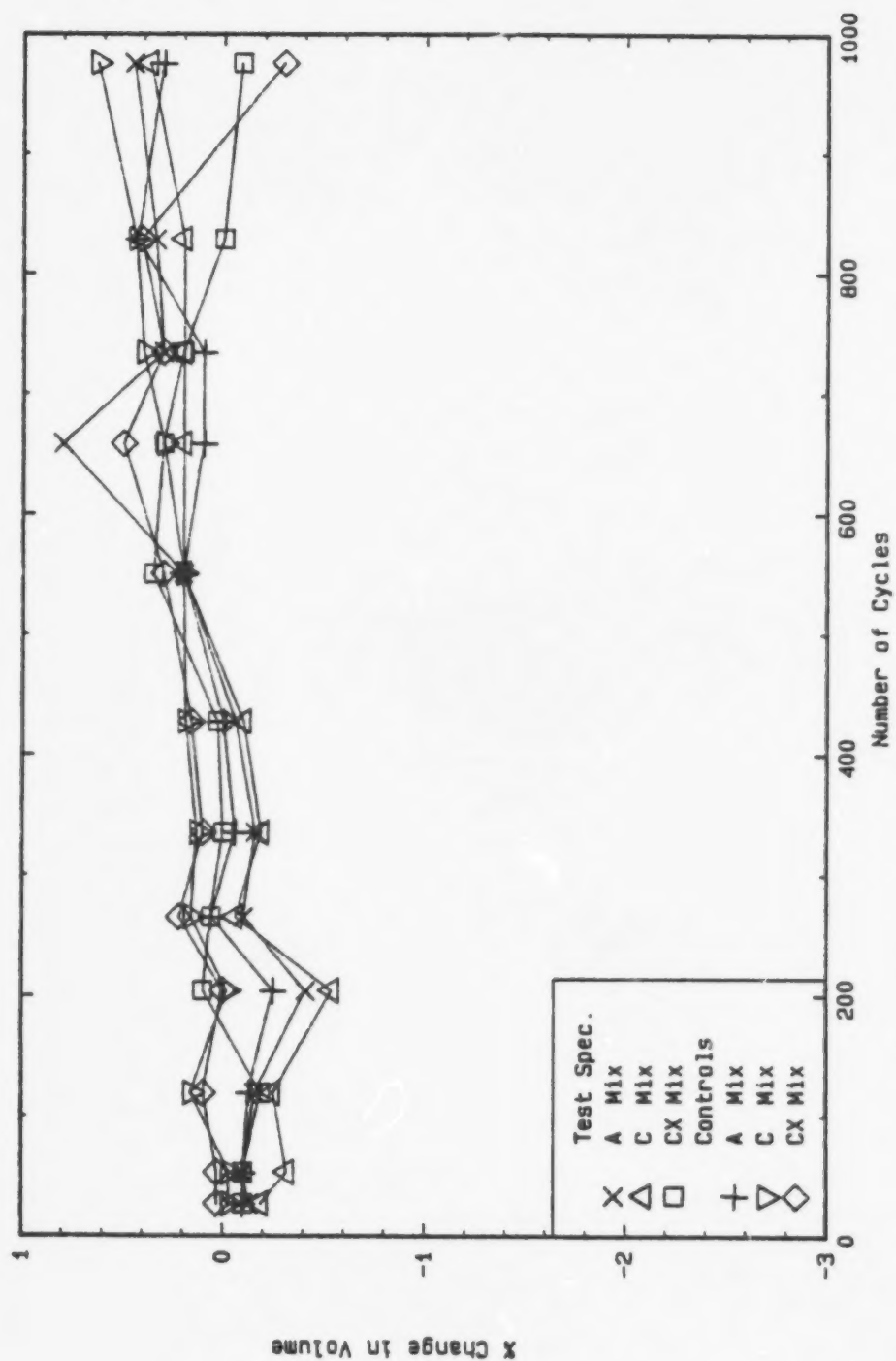


Figure 17a: Percent Change in Volume vs Number of Cycles
Prismatic Specimens

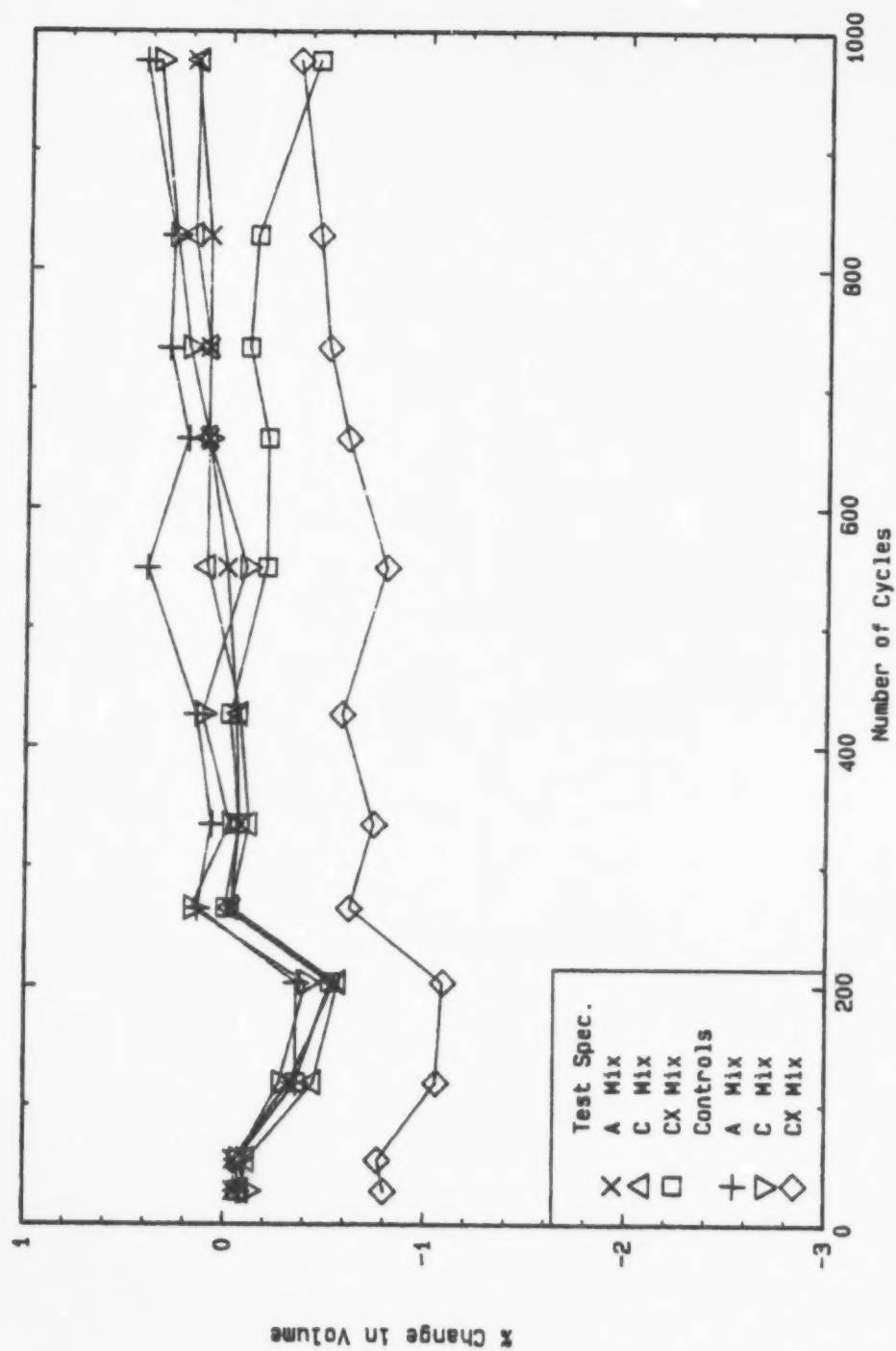


Figure 17b: Percent Change in Volume vs Number of Cycles
Cylindrical Specimens

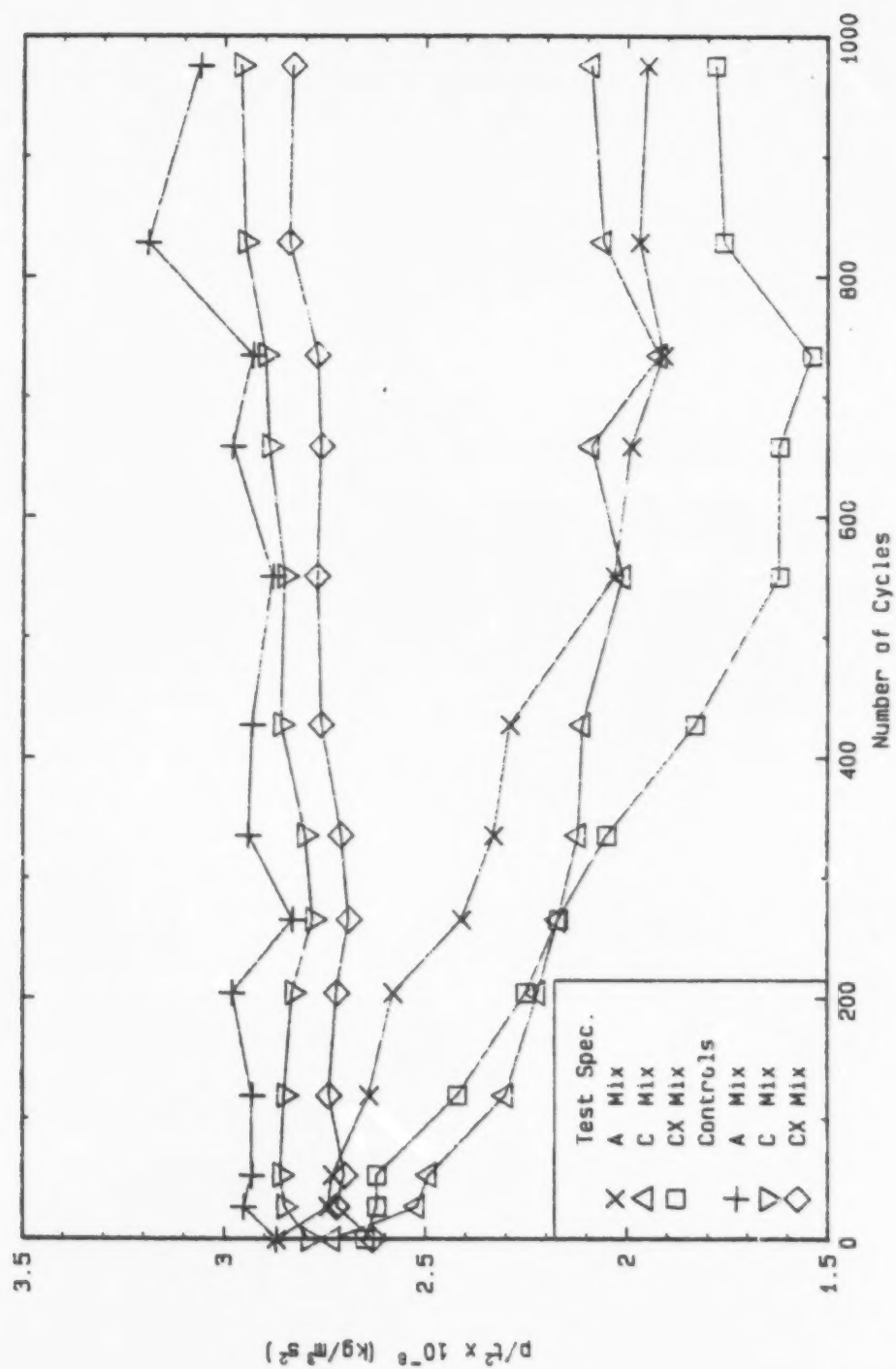


Figure 18a: p/t^2 vs Number of Cycles
Prismatic Specimens

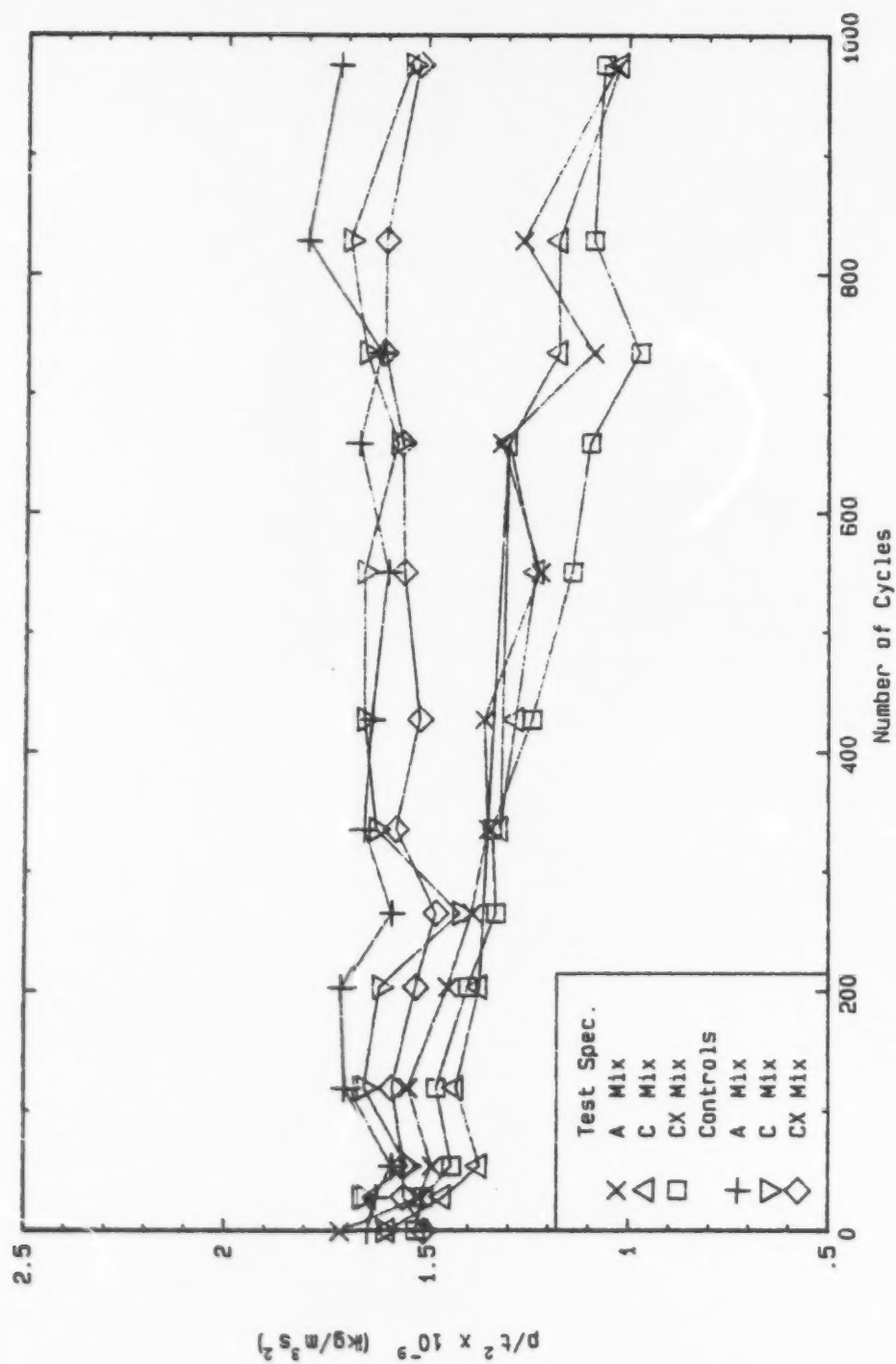


Figure 18b: p/t^2 vs Number of Cycles
Cylindrical Specimens

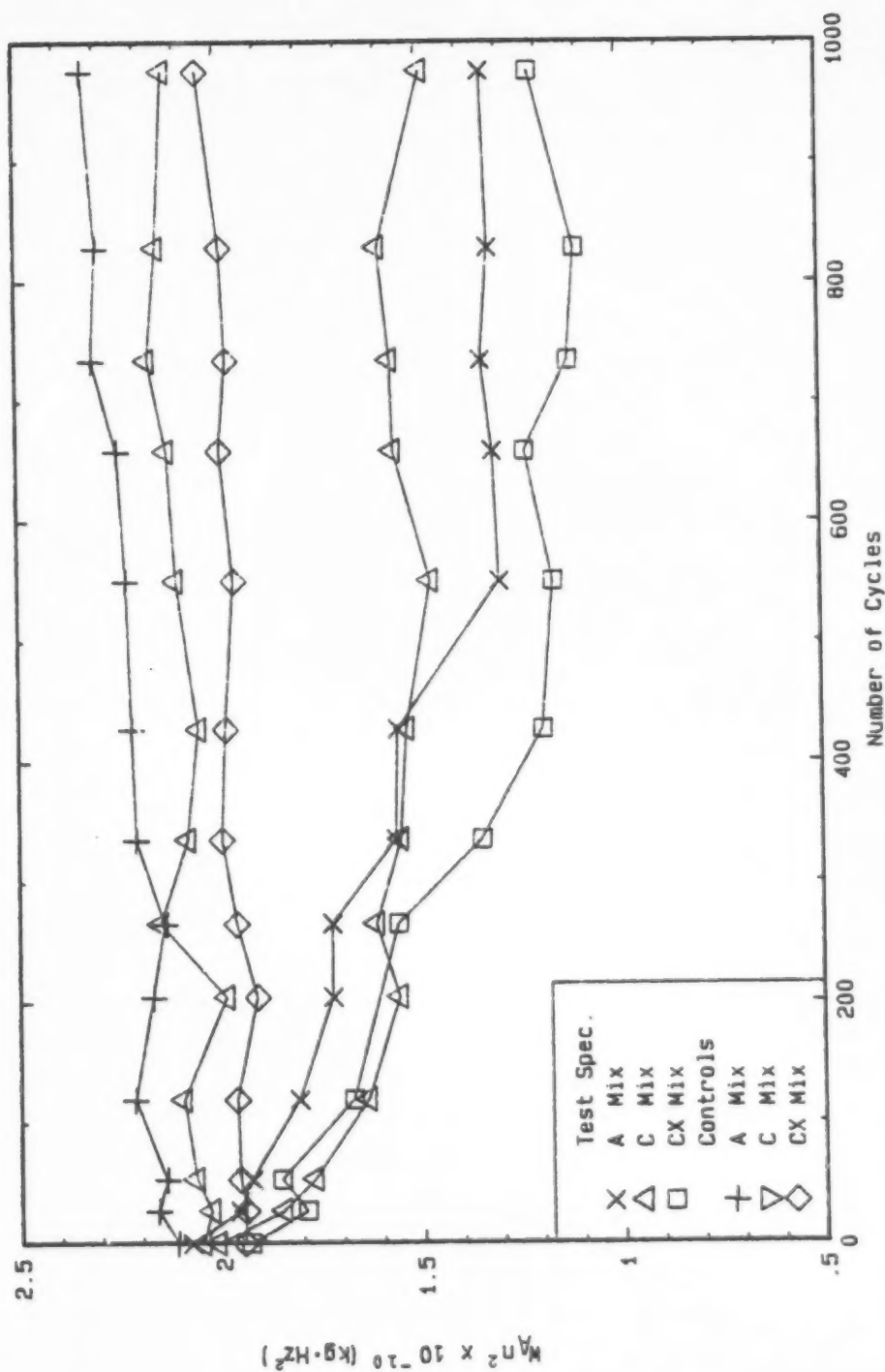


Figure 19: M_n^2 vs Number of Cycles
Prismatic Specimens

Included on these plots are the average results for the control specimens. However, for the controls the abscissa refers to the number of cycles to which the test specimens had been subjected when the control specimens were measured. This definition was necessary as the control specimens did not undergo cycling.

The standard deviation for the prismatic specimens was generally higher than that for the corresponding cylindrical specimens except for ρ/t^2 measurements. The standard deviation for the prismatic specimens also tended to increase during the course of the experiment. (Refer to Table 19b.)

The plots of percent change in weight (measured in air) for the prismatic specimens (Figure 14a) and the cylindrical specimens (Figure 14b) show that the weight of mix A and mix C specimens is decreasing, while the weight of mix CX specimens remained more or less constant. It also appears that mix C decrease more than mix A. Very similar behaviour is observed for the weight under water and density measurements for both prismatic and cylindrical specimens (Figures 15a through 16b). Table 19a indicates the average change of these variables over the course of the experiment.

The measured change in volume of the specimens was small when compared to changes in the other parameters, as indicated in Figures 17a and 17b and Table 19a. The observed change in the volume is insufficient to explain the observed decrease in weight. This is illustrated in Table 20 which shows the measured change in weight and the change in weight due to the decrease in volume. This Table was

RESPONSE VARIABLE	NO. OF CYCLES	A		C		CX	
		PRISMS	CYLINDERS	PRISMS	CYLINDERS	PRISMS	CYLINDERS
% Change in weight in Air	27	-0.5	-0.9	-1.0	-1.3	0.1	-0.4
	119	-1.5	-2.0	-2.6	-2.8	-0.1	-0.8
	265	-1.8	-2.2	-2.4	-2.6	0.4	0.0
	427	-2.7	-2.8	-3.2	-3.1	0.0	-0.2
% Change in weight in Water	27	-0.7	-1.4	-1.7	-2.2	0.3	-0.6
	119	-2.5	-3.2	-4.4	-4.5	0.0	-1.1
	265	-3.1	-3.9	-4.2	-4.5	0.7	0.0
	427	-4.6	-4.9	-5.5	-5.2	0.1	-0.3
% Change in Density	27	-0.4	-0.8	-0.9	-1.3	0.2	-0.3
	119	-1.3	-1.7	-2.3	-2.4	0.1	-0.5
	265	-1.7	-2.2	-2.3	-2.6	0.4	0.0
	427	-2.6	-2.8	-3.1	-3.0	0.0	-0.2
% Change in Volume	27	-0.13	-0.05	-0.19	-0.09	-0.10	-0.07
	119	-0.16	-0.33	-0.25	-0.45	-0.19	-0.36
	265	-0.10	-0.03	-0.06	-0.03	0.06	0.00
	427	-0.06	-0.05	-0.10	-0.07	0.03	-0.02
ρ/t^2 $\times 10^{-12}$, $\text{kg/m}^3\text{s}^2$	27	0.274	1.52	0.252	1.46	0.262	1.51
	119	0.264	1.55	0.230	1.43	0.242	1.48
	265	0.241	1.39	0.217	1.30	0.217	1.33
	427	0.229	1.36	0.211	1.28	0.183	1.24
$W_A n^2$ $\times 10^{-7}$, kgHz^2	27	1.96	-	1.85	-	1.79	-
	119	1.81	-	1.64	-	1.67	-
	265	1.72	-	1.61	-	1.56	-
	427	1.56	-	1.54	-	1.20	-

Table 19a: Change of the Response Variables over the course of Experiment

STANDARD DEVIATION OF...	NO. OF CYCLES	A		C		CX	
		PRISMS	CYLINDERS	PRISMS	CYLINDERS	PRISMS	CYLINDERS
% Change in weight in Air	27	0.2	0.1	0.2	0.2	0.1	0.1
	119	0.4	0.2	0.2	0.1	0.2	0.3
	265	0.5	0.1	0.4	0.1	0.4	0.2
	427	0.6	0.1	0.4	0.1	0.8	0.2
% Change in weight in Water	27	0.3	0.2	0.3	0.2	0.1	0.1
	119	0.8	0.3	0.3	0.2	0.2	0.3
	265	0.9	0.2	0.7	0.1	0.6	0.3
	427	1.0	0.2	0.7	0.2	1.1	0.4
% Change in Density	27	0.3	0.1	0.2	0.1	0.1	0.1
	119	0.5	0.2	0.3	0.1	0.1	0.2
	265	0.5	0.1	0.4	0.1	0.2	0.2
	427	0.6	0.2	0.4	0.1	0.5	0.2
% Change in Volume	27	0.11	0.04	0.08	0.06	0.09	0.03
	119	0.09	0.06	0.16	0.05	0.08	0.07
	265	0.06	0.05	0.08	0.07	0.25	0.02
	427	0.08	0.07	0.09	0.05	0.38	0.02
ρ/t^2 $\times 10^{-12}$, $\text{kg/m}^3 \cdot \text{s}^2$	27	0.01	0.03	0.01	0.04	0.004	0.02
	119	0.01	0.02	0.004	0.04	0.01	0.05
	265	0.02	0.04	0.01	0.08	0.01	0.08
	427	0.02	0.08	0.01	0.01	0.01	0.07
$W_A n^2$ $\times 10^{-7}$, kgHz^2	27	0.05	-	0.04	-	0.08	-
	119	0.12	-	0.09	-	0.09	-
	265	0.17	-	0.09	-	0.08	-
	427	0.14	-	0.09	-	0.13	-

Table 19b: Standard Deviation of Response Variables over the course of the Experiment

MIX	A		C		CX	
NO. OF CYCLES	ΔW_A , g	$\rho \Delta V$, g	ΔW_A , g	$\rho \Delta V$, g	ΔW_A	$\rho \Delta V$, g
PRISMS						
27	-33	-9	-74	-14	+10	-7
119	-111	-11	-188	-18	-6	-14
265	-131	-7	-173	-5	+32	+5
427	-194	-5	-233	-7	+3	+2
CYLINDER						
27	-117	-7	-187	-12	-54	-9
119	-274	-44	-386	-60	-110	-50
265	-309	-5	-361	-5	+2	0
427	-391	-7	-425	-9	-28	-2

Table 20: Average Change in Mass Measured and due Change in Volume

developed by evaluating the product of the absolute change in volume and the observed density ($\rho\Delta V$). The change in mass due to the change in volume is an order of magnitude lower than that observed by direct weight measurements. Consequently, the decrease in mass (and density) must be due to some internal form of leaching. Furthermore, since density is defined as mass per unit volume, the observed decrease in density cannot be a result of specimen expansion (volume remains comparatively constant).

Plots of ρ/t^2 from transit time measurements and $W_A n^2$ from resonant frequency measurements (Figures 18a, 18b, and 19) show remarkably different trends than the weight and density measurements. In fact, at 975 cycles the CX mix has been most greatly affected by exposure to wet/dry cycling. The average change in $W_A n^2$ for mix CX was 74% while the average change for mix A and C were 52% and 48% respectively.

Visual inspection also revealed that the CX specimens had the most surface deterioration. Furthermore, specimens from mix A showed better resistance to surface deterioration than specimens from mix C. Figures 20a, 20b, and 20c show typical cylindrical specimens from mixes A, C, and CX respectively. The exposed specimen is shown on the right of a control specimen. From these photographs it is also evident that the area of greatest deterioration occurred just above the waterline. The prismatic specimens showed similar surface deterioration but did not show the extreme deterioration at the waterline since they were totally submerged during the wet portion of the cycle.

In all cases the control specimens showed relatively constant behaviour with some fluctuations about the original value (see

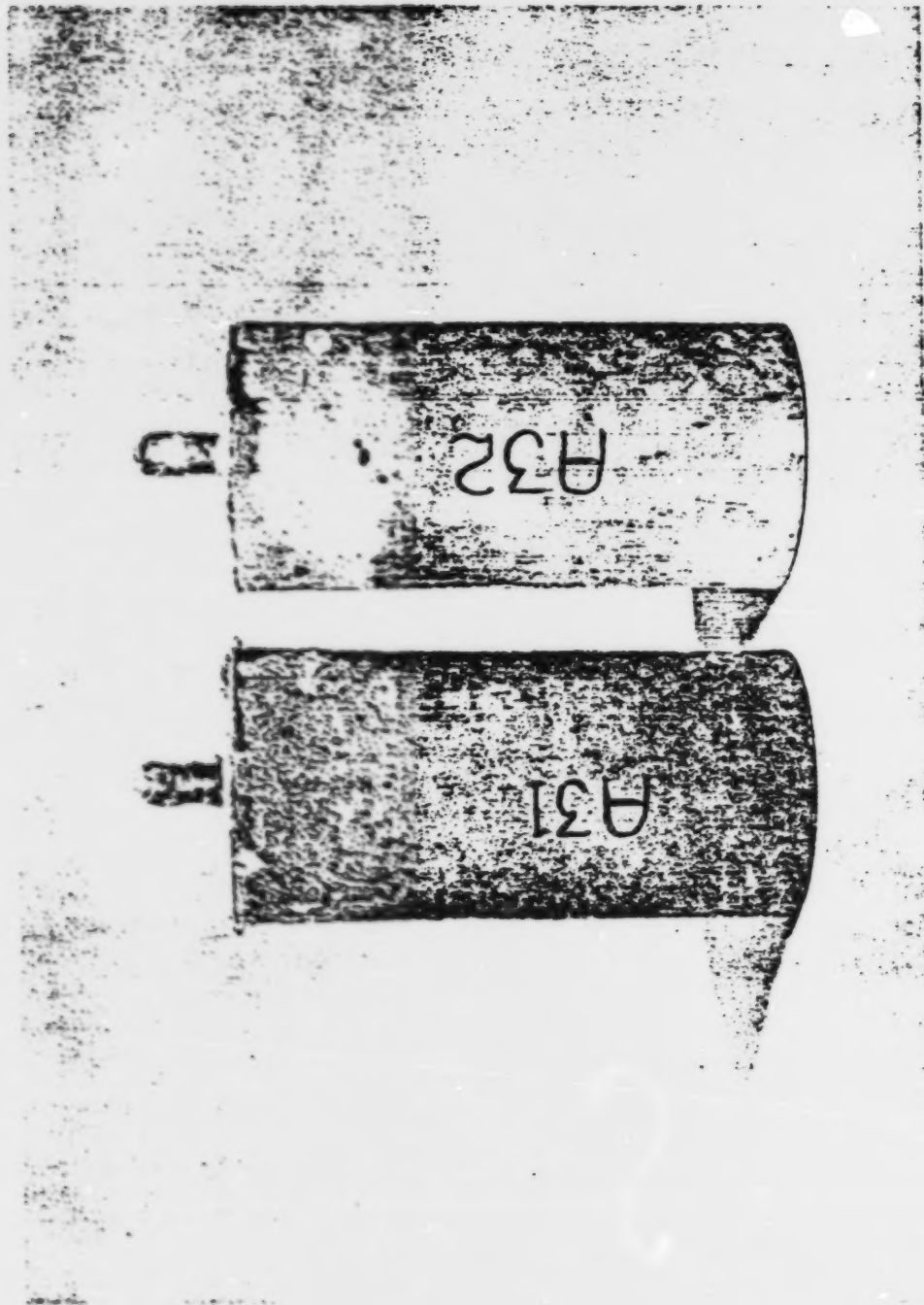


Figure 20a: Surface Condition of Mix A Specimen after Exposure

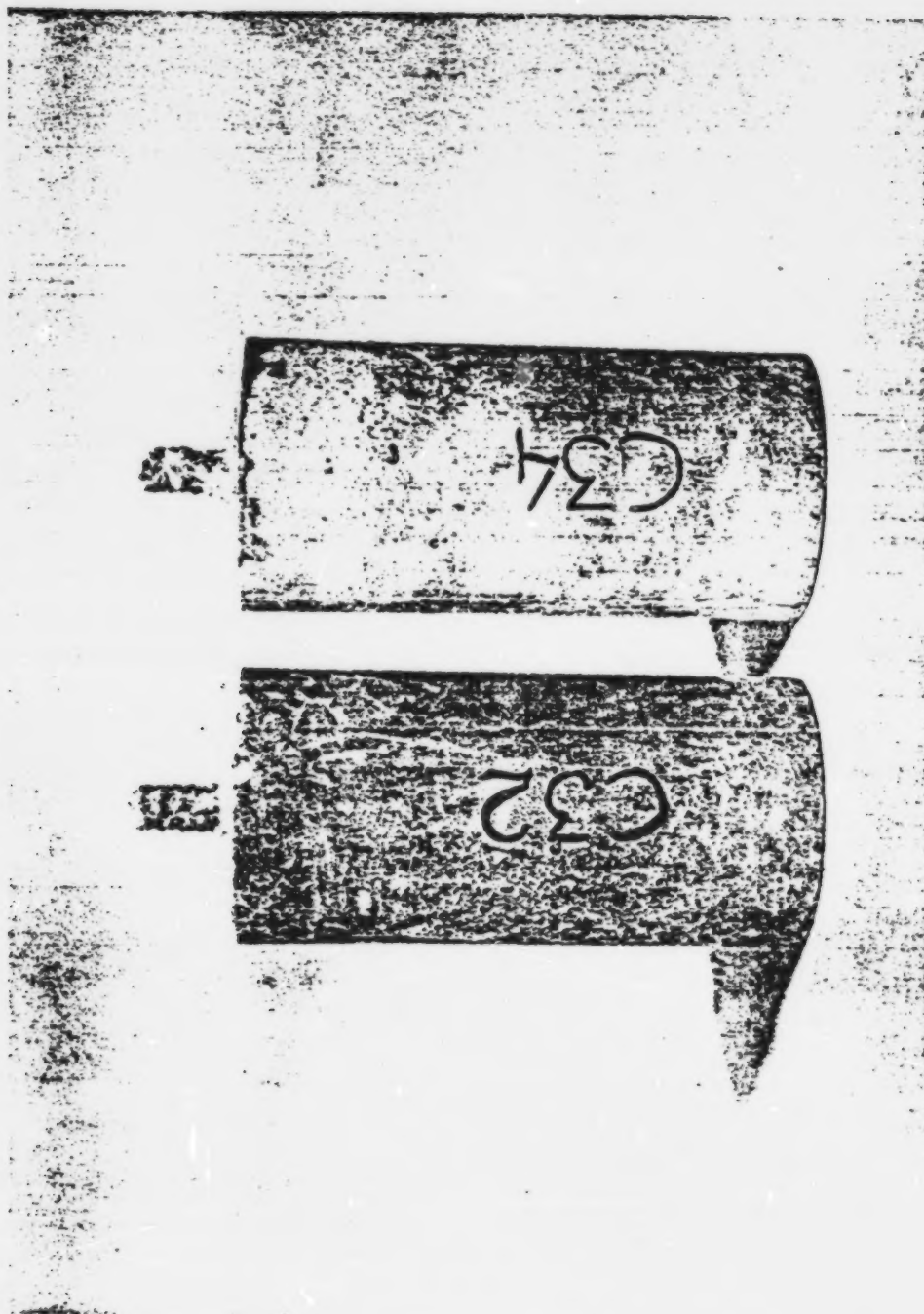


Figure 20b: Surface Condition of Mix C Specimen after Exposure

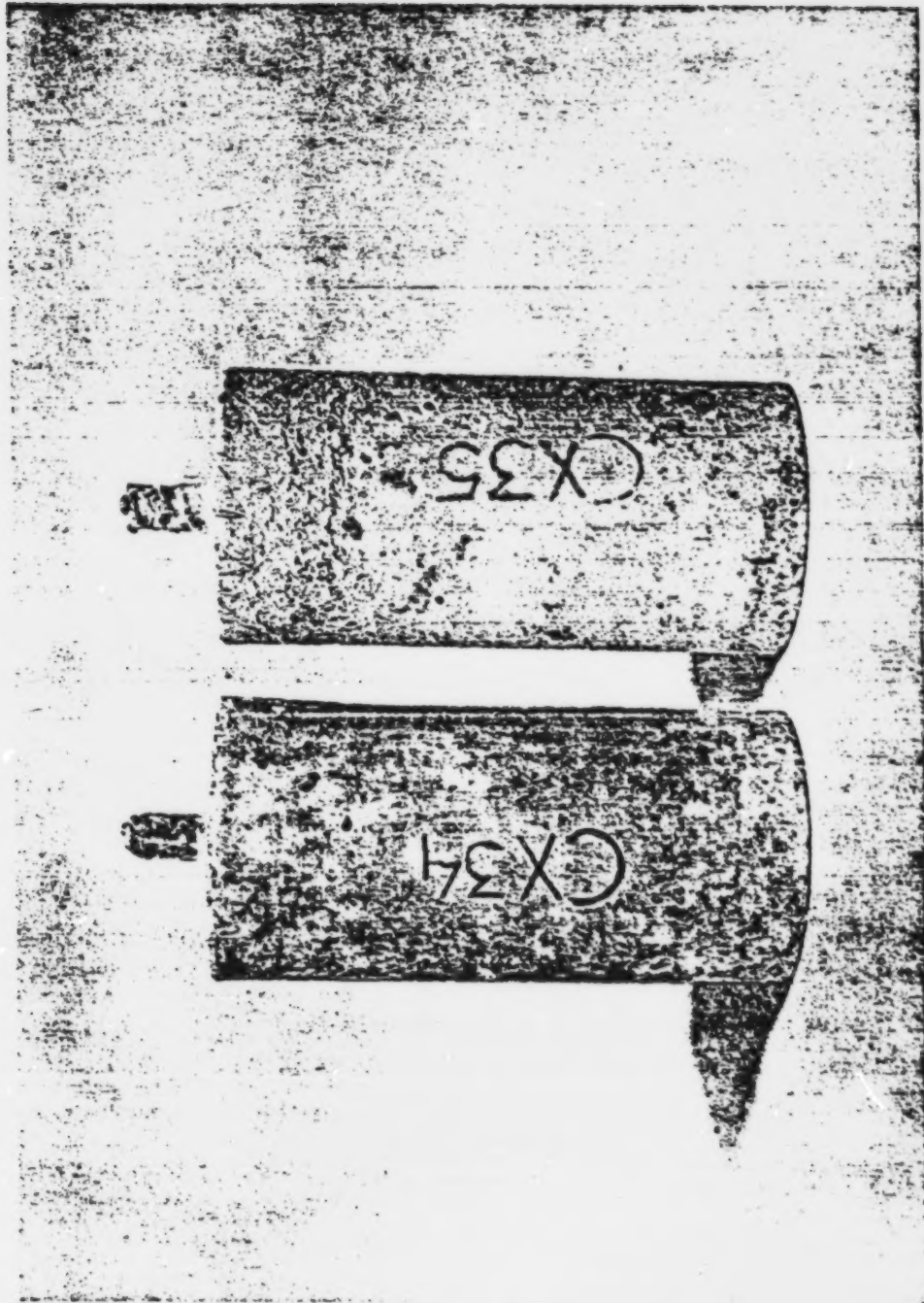
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Figure 20c: Surface Condition of Mix CX Specimen after Exposure

Figures 14a through 19). This confirms that the control specimens underwent little or no change when left in the moist cure room. Further, changes which were observed can be attributed to the test specimens being subjected to the wet/dry cycles.

Considerable surface erosion from the CX specimens was detected; this resulted in material loss from the surface of the specimens. This observation appears to be inconsistent with the observed weight change measurements, which show that the CX specimens have remained almost constant throughout the experiment. (Refer to Figures 14a and 14b and Table 19a.) This anomalous behaviour may be the result of two offsetting trends. The first is the loss of material from the specimen surface. The second is the mass uptake of salt and/or solution. Some evidence to support such a phenomenon was uncovered when specimens A32, C38, and CX35 were broken at the end of the experiment. Examination of the inner portions of the specimens revealed that a faint layer, approximately 2 cm thick, extended inwards from the surface of specimen CX35. This layer appeared to be the result of salt diffusion into the specimen. Such a layer was not observed in either A32 or C38.

The inner core of specimen CX35 also provided two other interesting observations which did not appear in either A32 or C38; first, the inner surface of the specimen was moist to the touch after fracture; and second, the inner core of the specimen was a very dark color (see Figure 21).

Examination of the steel reinforcement bars from specimens A32 and C38 did not show any evidence of the formation of iron oxide corrosion products. There was also good adhesion between the hardened cement paste and the steel. In contrast, the steel

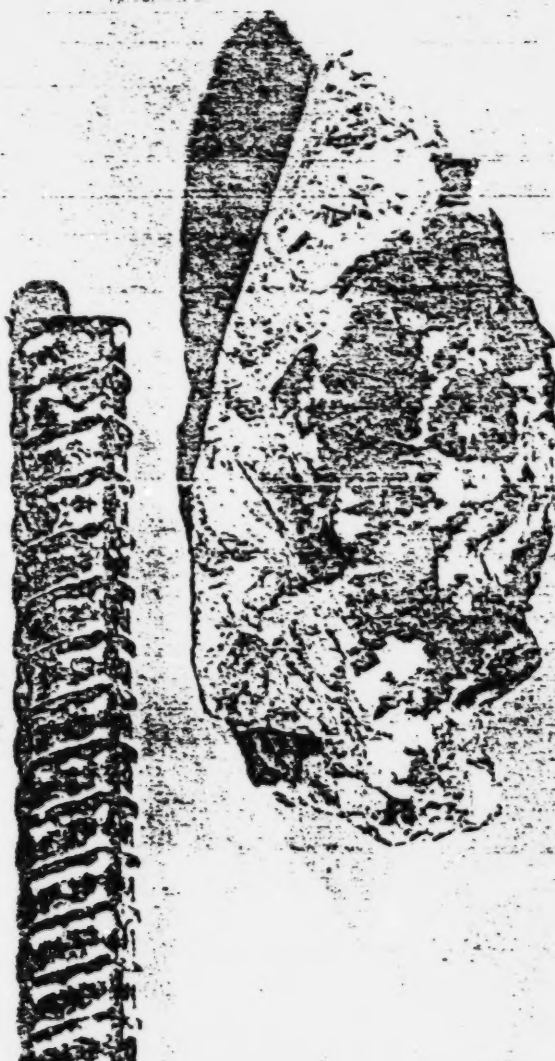
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Figure 21: Exposed Steel Reinforcement and Inner Core of Specimen CX35 after Exposure

reinforcement bar from specimen CX35 showed some formation of iron oxide and the bond between the hardened cement paste and the steel was comparatively poor. The formation of iron oxide on the steel reinforcement bar from specimen CX35 is illustrated in Figure 21.

5.2.2 Corrosion Potential Measurements

Corrosion potential measurements versus the number of cycles, are presented in Figures 22a, 22b, and 22c for the four specimens made from each mix. The corrosion potentials of all the specimens from mix A and mix C quickly achieve a steady state value between 90 and 190 mV (SHE). This would indicate that all of these specimens are in a passive or noncorroding state. Examination of the steel bars from A32 and C38 showed no signs of corrosion.

Corrosion potential measurements on the steel reinforcement in specimens made from mix CX are presented in Figure 22c. It is evident that these potentials are significantly different from those noted above. Potentials observed for these four specimens showed much greater variation. Three specimens (CX31, CX36 and CX37) eventually attained potentials similar to those observed on specimens made from mixes A and C. The fourth specimen (CX35) failed to achieve this potential. After some 400 cycles the potential of the specimen was -250 mV (SHE). According to studies by Hill et. al.^{32,33} (refer to section 2.11), this low corrosion potential value would indicate that specimen CX35 is in a state conducive to corrosion. The iron oxide observed on the reinforcement in specimen CX35 after breakage confirms the result of the corrosion potential measurements. As noted earlier, Figure 21 illustrates this corrosion.

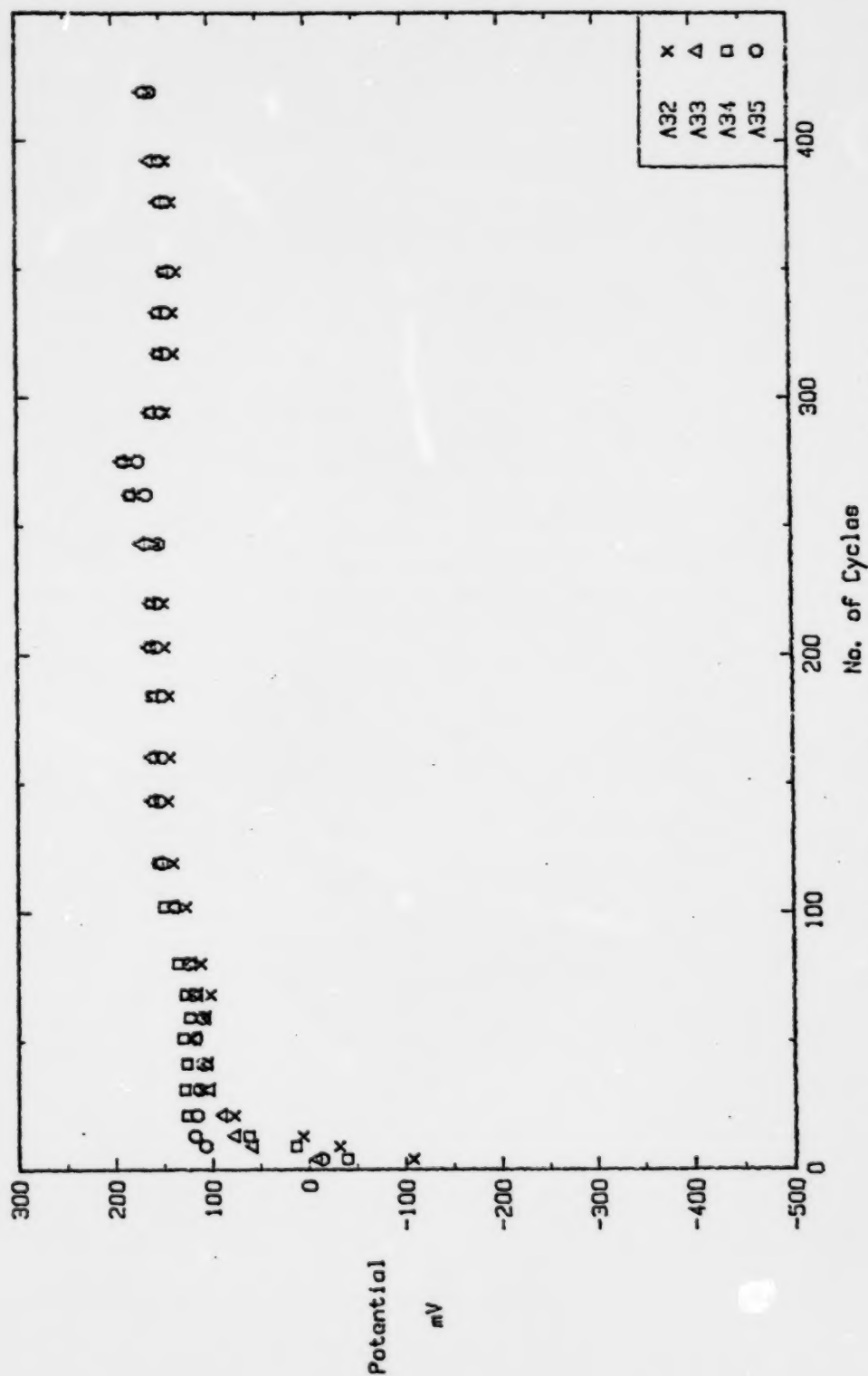


Figure 22a: CORROSION POTENTIAL VS NO. OF CYCLES
SHE REFERENCE
MIX A

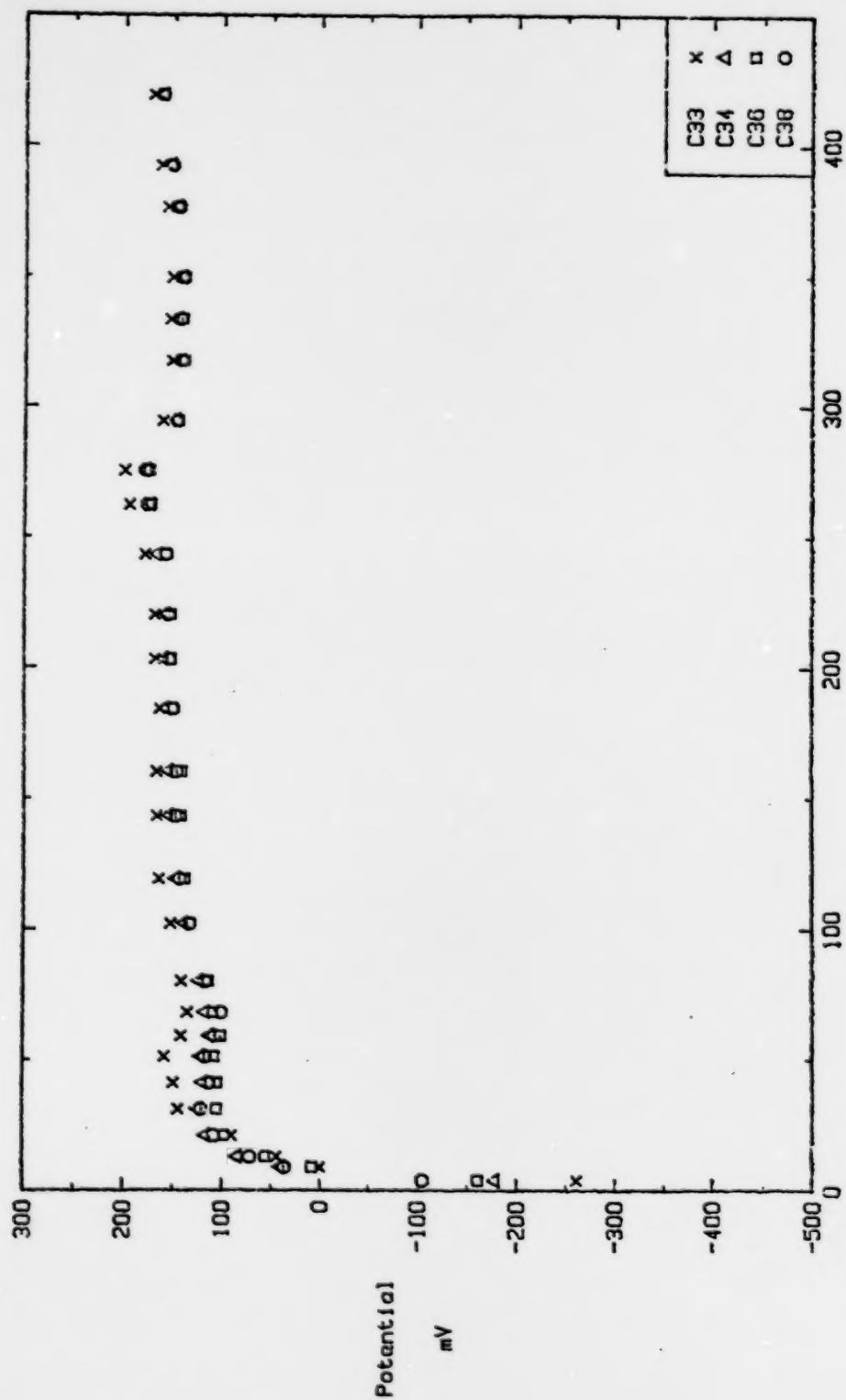


Figure 22b: CORROSION POTENTIAL VS NO. OF CYCLES
SHE REFERENCE
MIX C

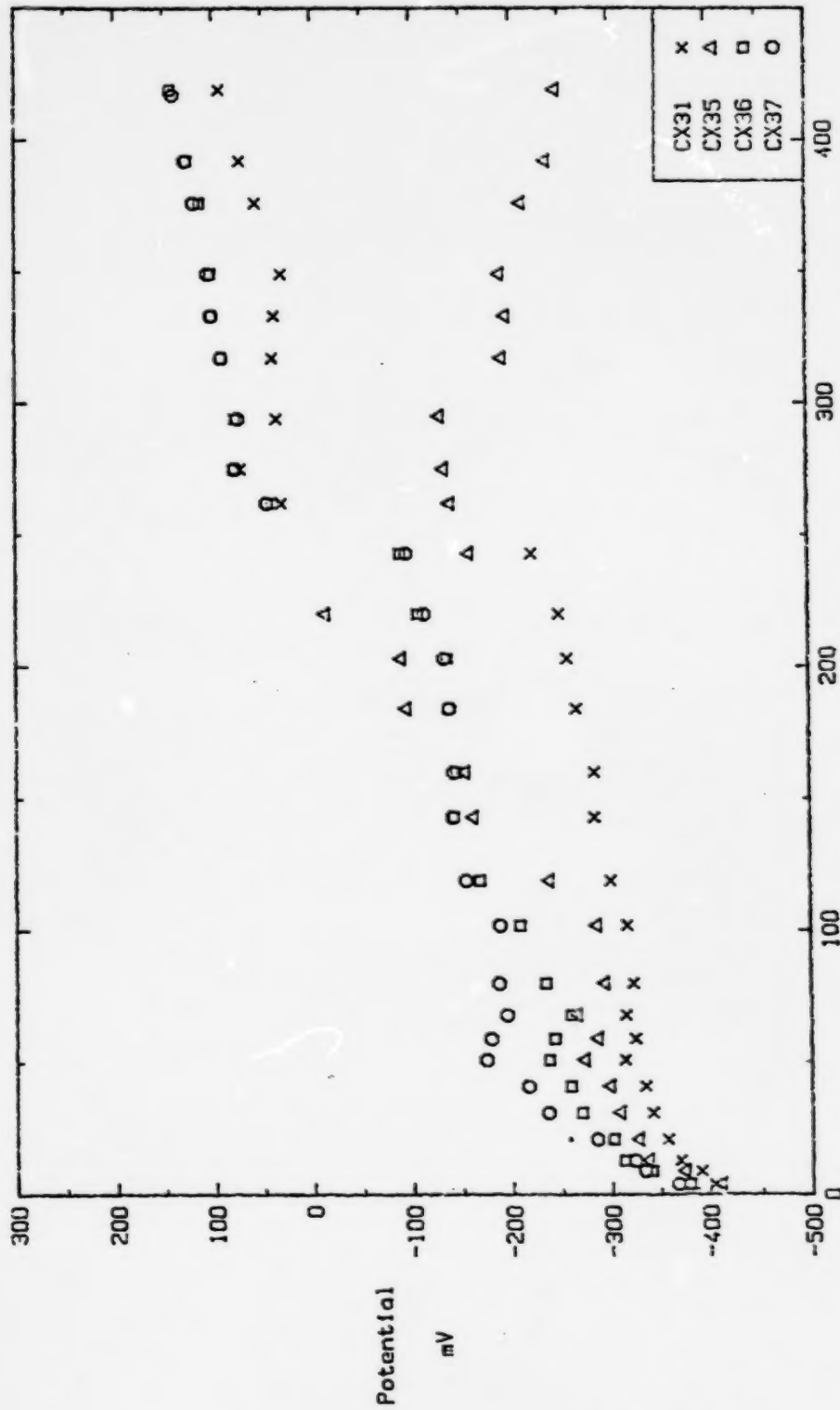


Figure 22c: CORROSION POTENTIAL VS NO. OF CYCLES
SHE REFERENCE
MIX CX

5.2.3 Strength Measurements

The strength tests were performed at the beginning of the accelerated durability test on three cylinder replicates and on three prism replicates. These corresponded in size to the cylindrical and prismatic specimens used in the accelerated durability test. The cylindrical specimens were tested in compression and the prismatic specimens were tested in third point flexure according to CA3-A23.2-M77 methods of testing of concrete. None of the specimens used for strength tests contained any steel reinforcement. In addition, two prismatic specimens from each mix were broken in the flexural mode after being exposed to 427 cycles. The results of the strength tests are presented in Table 21.

These strength tests confirm expectations. Mix A has a higher strength (39.7 MPa for cylinders, 6.1 MPa for prisms) than mix C (30.0 MPa for cylinders, 4.8 for prisms). In addition mix C shows a slightly higher strength than mix CX (26.6 MPa for cylinders, 4.3 MPa for prisms). Due to the limited number of specimens tested after cycling, it is not possible to draw any conclusions.

At the completion of 975 cycles all remaining prisms were tested in flexural and the results were given in Table 21. It would appear that after 975 cycles all concrete mixtures are seriously affected by the exposure to seawater.

BEGINNING OF ACCELERATED DURABILITY TEST							
FLEXURAL STRENGTH IN MPa				COMPRESSIVE STRENGTH IN MPa			
NO	MIX	A	C	CX	A	C	CX
1		6.4	5.4	4.2	39.5	29.3	26.8
2		6.1	4.6	4.5	38.9	32.0	26.7
3		5.7	4.3	4.2	40.7	29.0	26.8
	Avg.	6.1	4.8	4.3	39.7	30.0	26.6
	Std.Dev.	0.4	0.6	0.2	0.9	1.6	0.4
AFTER EXPOSURE TO 427 CYCLES							
NO	MIX	A	C	CX			
1		5.6	5.3	2.7			
2		5.3	5.2	4.2			
	Avg.	5.4	5.2	3.4			
AFTER EXPOSURE TO 975 CYCLES							
NO	MIX	A	C	CX			
1		0.9	4.0	0.6			
2		3.7	4.4	2.2			
3		1.1	1.1	-			
4		-	1.6	-			
	Avg.	1.9	2.8	1.4			

Table 21: Results of Strength Tests before and after the
Accelerated Durability Test

5.3 DISCUSSION

The results which were obtained from the accelerated durability test were both interesting and informative. These results show that it is possible to distinguish between the high quality mix, A, and poor quality mix, C. The poor quality mix showed a greater change in four of the six monitored variables. These variables were: weight in air, weight under water, density, and ρ/t^2 . Of the remaining two variables (volume and $W_A n^2$) the volume remained more or less constant over the course of the experiment, while values of $W_A n^2$ were almost coincidental at the beginning and end of the experiment. Visual inspection of the exposed surfaces also reveal that mix A has superior resistance to chemical attack by seawater salts.

Mix A and mix C are very similar in that specimens from both mixes are composed of the same constituents. The distinguishing feature being that mix A has a W/C of 0.4 while the ratio for mix C is 0.6. As a result, it is not surprising that the specimens from these mixes show similar behaviour. The trends are identical, however, the change of the response variable is more pronounced in the case of C than in the case of A.

When a slag constituent is used to replace the cement (mix CX) the fundamental nature of the specimen is altered. The measured response variables show a dramatic change in comparison to that of mix A and mix C. The measurements of weight in air, weight under water, and density stay much more constant than is the case for mixes A and C. From these measurements the conclusion that mix CX is superior to that of either A or C could be drawn if not for other conflicting results. Measurements from both the resonant frequency ($W_A n^2$) and the

transit time (ρ/t^2 and $W_A n^2$ data on the prismatic specimen of mix CX show that these specimens have been affected to a greater degree than either mix A or mix C specimens.

Visual inspection revealed that the CX mix specimens were highly susceptible to chemical attack by salts contained in seawater. From Figures 20a, 20b, and 20c, which compare the surface deterioration of mix A, C, and CX respectively, it can be seen that the slag containing mix has by far the most inferior resistance to surface attack and erosion.

A further indication of the poor nature of the slag containing mix was revealed when specimen CX35 was broken (after 427 cycles). The inner surface of the specimen was found to be moist and the inner core was an uncharacteristically dark color. There are two possible mechanisms which could explain the presence of moisture. In the first case, the moisture could be the result of incomplete hydration of the mixture containing slag. Great care was employed to ensure that proper curing of the specimens occurred. The specimens were allowed to moist cure at room temperature for 114 days before the accelerated test was begun. The accelerated test lasted 5 months before the specimen was broken open. Thus, there was a period of almost nine months between the mixing of the concrete and its subsequent destruction. The second manner by which free moisture could have been introduced into the specimen is through the diffusion of water from the wet portion of the cycle.

Evidence can be found in the experiment in support of each mechanism; however, in neither case does the evidence conclusively confirm or discredit either mechanism. In the former case, incomplete

hydration would give rise to a reduced strength. This was observed since CX exhibits a reduced strength compared to mix C. However, the weight in air measurements of mix CX remain constant in contrast to the observed decrease for mix A and C. One of the possible explanations for the constant weight measurements is that two offsetting trends coexist. Material is being leached from the specimen giving rise to a reduction in weight, but the absorption of salt and solution compensates for this weight loss. This hypothesis supports the presence of free moisture through absorption from the wet portion of the cycle.

The standard deviation of the individuals for the prismatic specimens is greater than for the cylindrical specimens. This holds true for weight in air, weight under water, and density measurements. The explanation of this phenomenon appears to be a result of the different molds used to cast the prisms. Specimens numbered 43 and 44 from each mix were cast using wooden molds, whereas specimens numbered 49 and 410 were cast from metallic molds. (The cylindrical specimens were all cast using identical plastic molds.) The ability of wood to absorb water could conceivably affect the W/C ratio thereby influencing the durability of the specimen.

A standard statistical technique of comparing two sample means is used to determine if there exists a significant difference between the measured results of specimens from the metallic and wooden molds. (Appendix V illustrates the technique employed.) A 95% confidence interval was derived for the difference between the sample means for the metallic and wooden molds for each response variable. The null hypothesis was that the means are equal ($\mu_1 = \mu_2$), while the alternative hypothesis was that the means are different ($\mu_1 \neq \mu_2$).

Table 22 presents the 95% confidence interval for difference in sample averages for each mix. For the null hypothesis to be valid the zero point should be contained within the confidence interval (that is $\mu_1 - \mu_2 = 0$). The alternative hypothesis is valid when the zero point is not contained within the confidence interval ($\mu_1 - \mu_2 \neq 0$). As is evident from Table 22 the alternative hypothesis is valid in a number of cases thus demonstrating that the use of wooden or metallic molds can influence the results.

The measurements of ρ/t^2 for the cylindrical specimens also had large associated errors although the reasons are quite different than those above. There existed considerable difficulties in obtaining the transit time measurements of the cylinders in the radial direction due to the curved surface of the specimens. The uncertainty was further compounded as the path length through the cylindrical specimens was roughly 1/2 that of the prismatic specimens.

Monitoring the control specimens concurrently with the test specimens confirmed that any changes detected in the specimens was a direct result of the accelerated testing sequence and not due to continuing hydration or any other phenomena occurring naturally within the concrete. The control specimens have remained relatively constant.

Monitoring the corrosion potentials of the steel reinforcing specimens was not entirely successful. All specimens from mix A and mix C quickly achieved a steady state value between 90 and 190 mV thereby indicating a passive or non-corroding state. The passive state then remained constant for the remainder of the experiment. It was predicted that corrosion of the steel reinforcement would be induced in the specimens by chloride diffusion to the steel/concrete interface.

RESPONSE VARIABLE	MIX A		MIX C		MIX CX	
	95% Confidence* Interval	Correct [†] Hypothesis	95% Confidence Interval	Correct Hypothesis	95% Confidence Interval	Correct Hypothesis
% Change in weight in Air	0.14 to 1.36	ALT.	-0.83 to 0.49	NULL	-0.82 to -0.28	ALT.
% Change in weight under Water	0.28 to 2.42	ALT.	-1.37 to 0.93	NULL	-1.07 to -0.13	ALT.
% Change in Density	0.17 to 1.41	ALT.	-0.67 to 0.65	NULL	-0.43 to 0.26	NULL
$\rho/t^2 \times 10^{-8}$, kg/m ² .s	0.08 to 0.40	ALT.	-0.21 to 0.11	NULL	-0.16 to 0.28	NULL
$W_A n^2 \times 10^{-10}$, kg.Hz ²	0.29 to 0.30	ALT.	-0.184 to 0.070	NULL	-0.150 to 0.268	NULL

* 95% Confidence Interval for the difference in averages for specimens from wooden and from metal molds
($\bar{y}_1 - \bar{y}_2$)

+ NULL HYPOTHESIS - states that the means for specimens from wooden and from metallic molds to the same
($\mu_1 = \mu_2$)

ALTERNATIVE HYPOTHESIS - states that the means for specimens from wooden and from metallic molds is
different ($\mu_1 \neq \mu_2$)

Table 22: 95% Confidence Interval for Specimens from Wooden and Metallic Molds.

Ideally a corrosion state would first be detected in mix C specimens followed by mix A specimens. Such an observed result would indicate a higher permeability to Cl^- of mix C compared to mix, A. This trend was not noted and probably indicates that the initial cover was too great or the tests were not run long enough.

The corrosion potential behaviour of the CX mix specimens show a different trend than specimens from mixes A and C. The interpretation of the corrosion potentials is not evident, but it appears that three of the specimens (CX31, CX36, and CX37) were in a passive state while specimen CX35 was in an active corrosion state. The depressed corrosion potentials of the CX mix specimens from the beginning of the experiment may be an indication that free moisture within the specimens existed from the beginning of the accelerated test. This would lend support to the proposal that free moisture was introduced via incomplete hydration. Furthermore, if water (and salts) could readily penetrate the concrete then corrosion could have been induced due to chloride diffusion thus causing all of the corrosion potentials to be low at the end of the experiment. Thus, the corrosion potentials indicate that the free moisture was not introduced by absorption of water during the wet portion of the cycle.

CHAPTER 6

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 ACCELERATED TEST VERSUS LONG TERM EXPOSURE

The three mixes which were evaluated in this study have corresponding equivalents which are currently undergoing long term exposure to the natural environment at Treat Island, Maine⁴⁶. Only prismatic specimens are used at Treat Island. These specimens measure 305 mm x 305 mm x 914 mm; this is considerably larger than the specimens used in the accelerated test. The specimens of the long term durability study are examined on a yearly basis by visual inspection and by the transit time of a sound pulse through the specimen. At the time of this report, the specimens had undergone 5 years of continuous exposure. The results of the sound pulse measurements are presented graphically as transit time per unit length versus number of exposure cycles. See Figure 23a. The number of cycles is estimated by using 2 cycles per day (2 tides per day) times 365 days per year. The transit time per unit length is also calculated for the prismatic specimens which were exposed to the accelerated test and is presented graphically in Figure 23b.

Comparison of the two sets of results shows the same trends. the initial values of the specimens are all in the same range (~ 0.230 $\mu\text{sec/mm}$). The specimens of the accelerated test show a gradual increase over the course of the exposure which is not as evident in the case of the long term durability study. The results of the long term exposure test for mix CX show a marked increase in the unit transit time after 2190 cycles (3 years). This appears to correspond to the observed

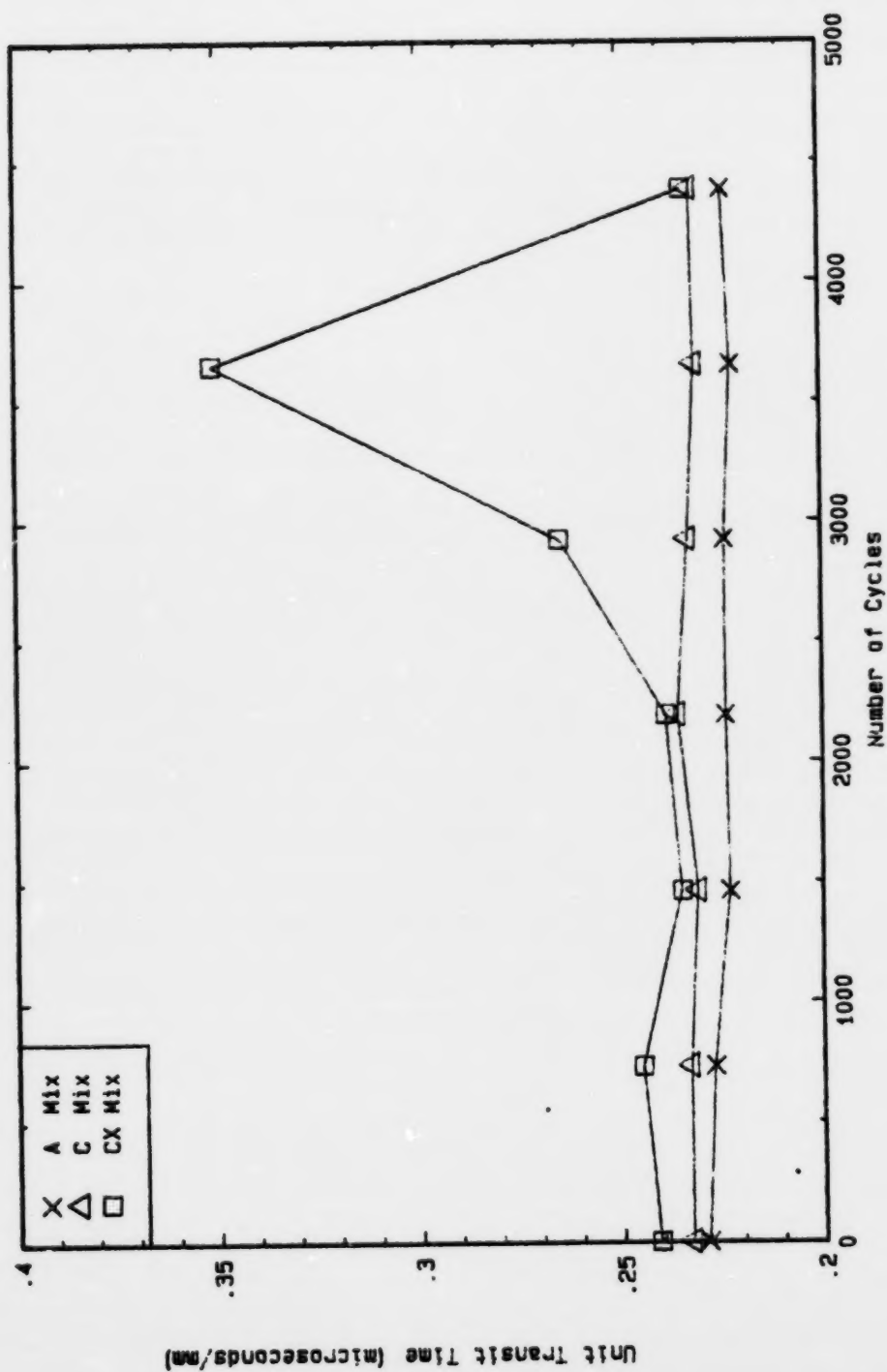


Figure 23a: Unit Transit Time vs Number of Cycles
Treat Island Specimens

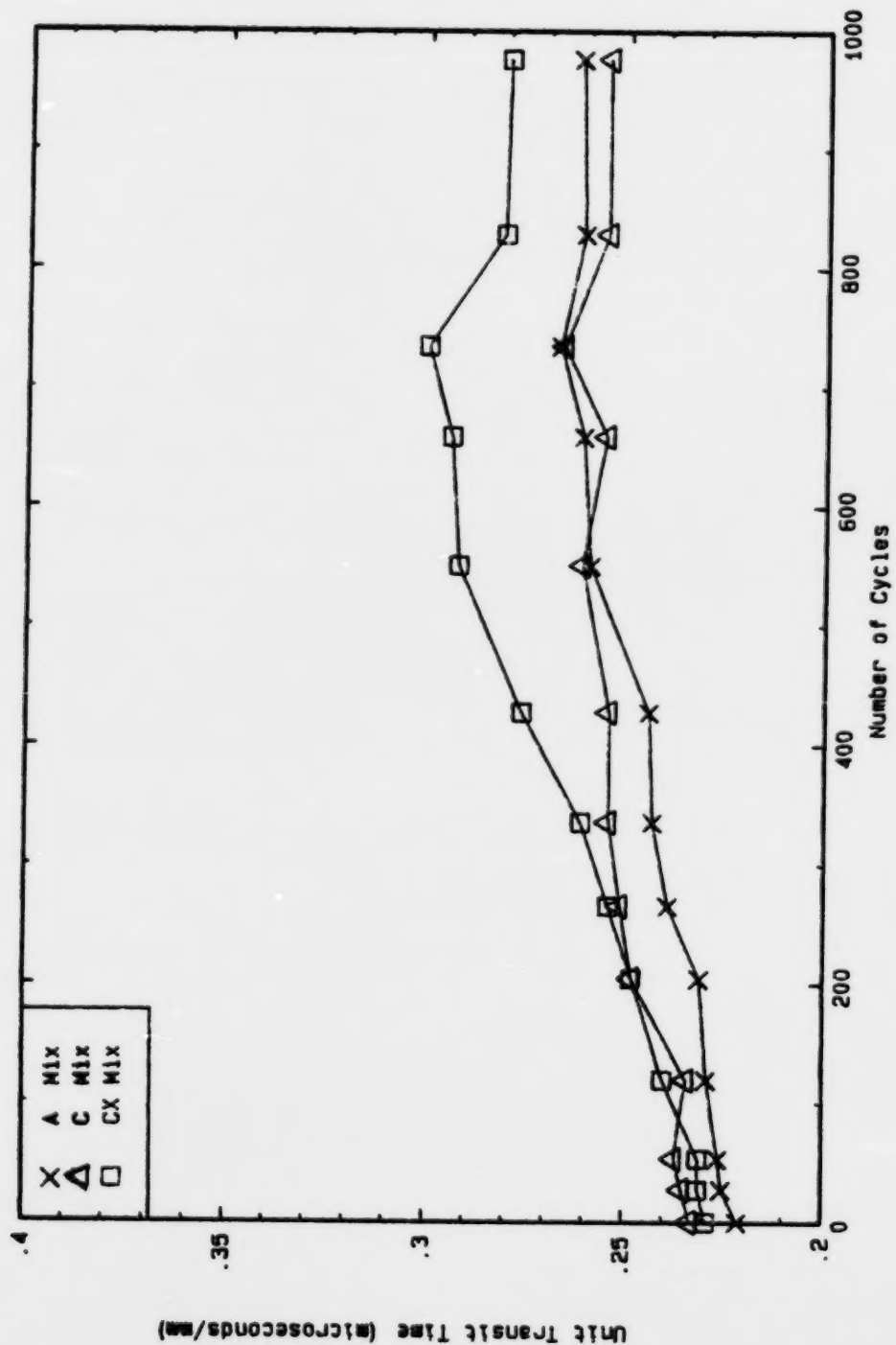


Figure 23b: Unit Transit Time vs Number of Cycles
Accelerated Test Specimens (Prisms)

increase at the end of the accelerated test, albeit the increase in the unit transit time measurements of the accelerated test are not as pronounced as in the case of the long term exposure test.

Comparing the surface conditions of the appropriate specimens from the accelerated test to the long term test (Figures 20a, 20b, and 20c to Figures 24a, 24b, and 24c respectively) indicates that the same general trends in regard to surface deterioration have occurred. Specimens from mix A show almost no sign of surface deterioration, whereas specimens from mix CX exhibit considerable signs of surface attack and erosion.

6.2 SUMMARY

The accelerated durability test was successful. The apparatus performed well with only an occasional minor malfunction. The results obtained from the accelerated durability test could be compared favourably to long term exposure results, although absolutely identical results did not occur. The accelerated durability test and the long term exposure study also show that similar trends exist between transit time measurements and visual inspection of the surface.

The monitored variables weight in air, weight under water, volume, density, transit time of a sound pulse, and resonant frequency proved to be sufficient to evaluate the durability of the concrete mixes which were tested. With these measurements it was possible to distinguish a difference in durability between various concrete mixes. It was found that concrete with a W/C ratio of 0.4 showed the best durability while concrete with a W/C ratio of 0.6 showed inferior durability.



Figure 24a: Surface Condition of Long Term Exposure Specimen
- Equivalent to Mix A



Figure 24b: Surface Condition of Long Term Exposure Specimen
- Equivalent to Mix C

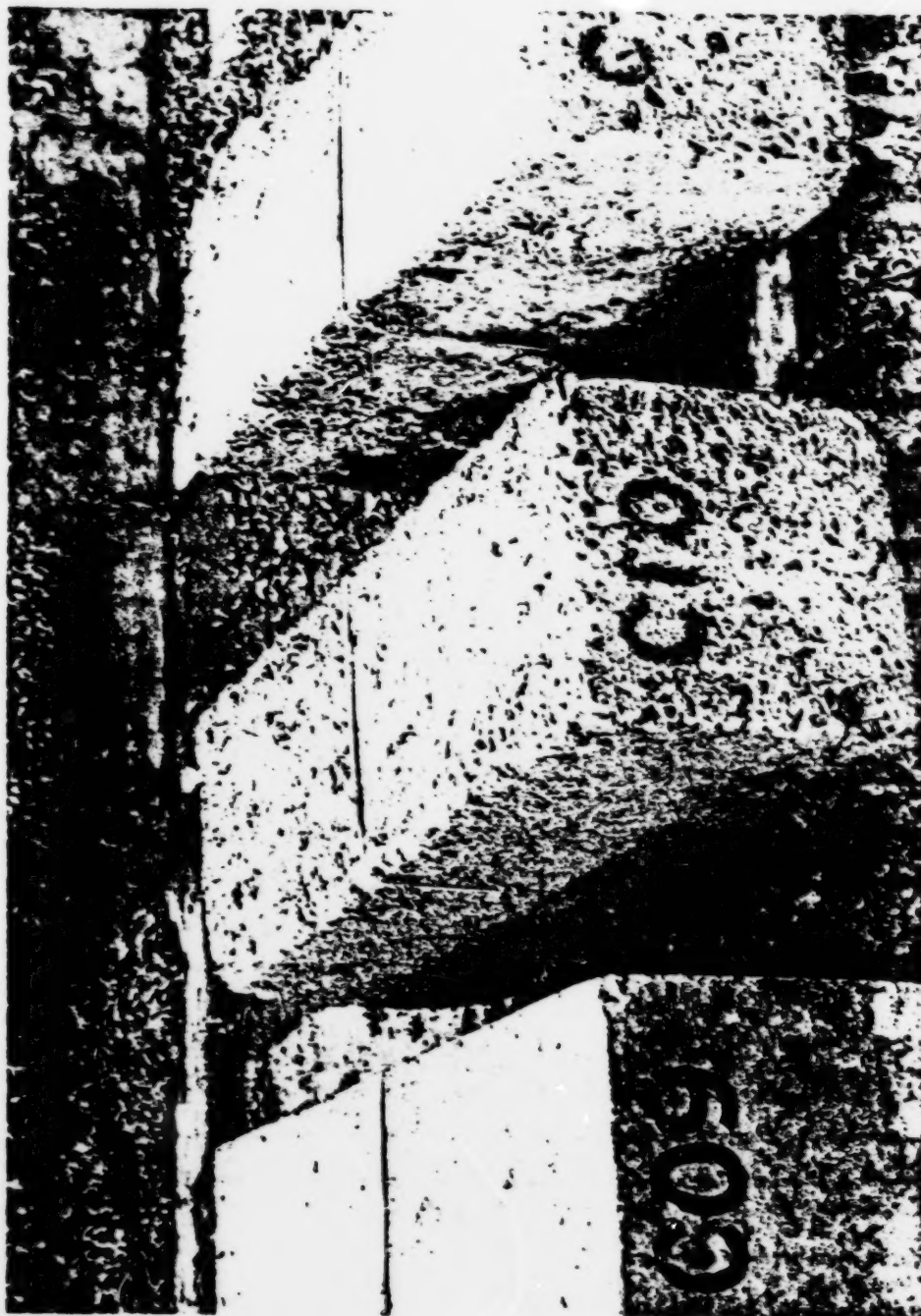


Figure 24c: Surface Condition of Long Term Exposure Specimen
- Equivalent to Mix CX

The accelerated test illustrated that 65% slag replacement for cement coupled with a W/C ratio of 0.6 had a detrimental effect on the durability of the concrete. However, this test does not prove that all slag types have the same detrimental effects on the durability.

6.3 RECOMMENDATIONS

Now that an accelerated method has been developed to evaluate the durability of concrete to seawater in an accelerated manner, a comprehensive series of tests should be carried out to evaluate all of the concrete mixes likely to be used in marine work. Also mixes identical to all those at Treat Island should be run to establish base line information in order that the results of the accelerated testing can be interpreted in a realistic way.

A more realistic method of testing the prisms may be to place them vertically in the seawater so that only one half is immersed. At various times the prisms can be tested for resonant frequency and also for flexural strength.

Although the corrosion testing equipment appeared to work well additional testing is required so as to identify optimum thickness of cover and positioning of the steel bar in the concrete cylinder.

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APPENDIX I

SOLUTION TO THE EQUATION OF NON-STEADY DIFFUSION IN A CYLINDER

Non-steady diffusion in a cylinder of infinite length can be described mathematically by ...

$$\frac{\partial^2 C}{\partial r^2} + \frac{1}{r} \frac{\partial C}{\partial r} = \frac{1}{D} \frac{\partial C}{\partial \theta} \quad \dots 1$$

C is the concentration,

r is the position variable (radius),

θ is the time variable, and

D is the diffusion coefficient

Boundary conditions:

- a) At the surface of the cylinder, r_0 , the concentration of the surroundings remain constant at C_∞
- b) At all times the concentration at the centre of the cylinder is a minimum. Thus, at this point the first derivative of C with respect to r is 0 for all times greater than or equal to zero ($\theta \geq 0$)
- c) Initially, the concentration throughout the cylinders is uniform at C_i .

Thus

$$C(r_0, \theta) = C_\infty \quad \dots 1a$$

$$C_r(0, \theta) = 0 \quad \dots 1b$$

$$C(r,0) = C_i \quad \dots 1c$$

Normalizing variables (normal variables are indicated by bars):

$$\begin{aligned} \bar{r} &= r/r_0 & \therefore r &= r_0 \bar{r} \\ \bar{C} &= C_i - C_\infty & \therefore C &= \bar{C}(C_i - C_\infty) + C_\infty \\ \bar{\theta} &= \frac{\theta D}{r_0^2} & \therefore \theta &= r_0^2 \bar{\theta} / D \end{aligned}$$

Normalization of variables are so defined that the normal variables are dimensionless. Furthermore, the normalized position and concentration variables vary between 0 and 1.

Substituting the normal variables into equation 1 and into the boundary conditions 1a, 1b, and 1c yields:

$$\frac{\partial^2 \bar{C}}{\partial \bar{r}^2} + \frac{1}{\bar{r}} \frac{\partial \bar{C}}{\partial \bar{r}} = \frac{\partial \bar{C}}{\partial \bar{\theta}} \quad \dots 2$$

and

$$\bar{C}(1, \bar{\theta}) = 0 \quad \dots 2a$$

$$\bar{C}_r(0, \bar{\theta}) = 0 \quad \dots 2b$$

$$\bar{C}(\bar{r}, 0) = 1 \quad \dots 2c$$

All variables at this point have been normalized, bars are dropped for convenience.

Assume separation of variables.

that is $C(r, \theta) = R(r) \cdot H(\theta)$

Thus, 2 becomes $R'' H + \frac{1}{r} R' H = R H'$

rearranging yields:

$$\frac{R''}{R'} + \frac{1}{r} R' = \frac{H'}{H} = \text{constant} = -\lambda^2$$

where λ^2 is a constant.

APPENDIX II

PREPARATION OF SPECIMENS

All of the specimens of the same mix were made in one batch with the exception of the small 25 mm ϕ x 50 mm specimens. These specimens were batched previous to all other specimens and were used only in the preliminary tests. Owing to the small size of these specimens they contained no coarse aggregate. For this reason and to distinguish these specimens from the larger ones they shall henceforth be referred to as mortar specimens. The constituents of the mortar specimens are presented in Table 1.

The mortar specimens were assigned a character code. This code consisted of a letter referring to the particular mix, either A, C, or CX, and a two or three digit number. The last digit refers to either replicate 1 or 2 and the first digit(s) refers to the particular test environment to which the specimen was exposed. This consists of series 1 through 16 and relates directly to the environments outlined in Table 15 of the main text.

	Mix Proportions	
	Cement: Slag: Sand	W/C
A- High Quality	1:0:1.76	0.40
C- Poor Quality	1:0:3.36	0.60
CX-Undetermined	1:2:9.59	0.60

Table 1: Mix proportions for mortar specimens

All other specimens were concrete, rather than mortar, and contained both fine and coarse aggregate. These specimens were considerably larger in size. The constituents of these mixes are presented in Table 2.

MIX	Cement, kg	Slag, kg	Water, kg	FA, kg	CA, kg	Air-entraining Agent (ml)
A	31.7	0	12.7	32.0	82.6	35.6
C	19.1	0	11.4	50.0	85.2	15.7
CX	6.7	12.4	11.4	48.4	40.9	19.2

Table 2: Mix Proportions of Concrete Specimens

The W/C ratio and percent slag were calculated and the percent air and slump were measured after mixing: these values are presented in Table 3.

MIX	W/C	% Slag	%Air	Slump (mm)
A	0.40	0	6.8	78
C	0.60	0	5.8	82
CX	0.60	65	6.6	90

Table 3: Calculated and Measured Properties of Concrete Specimens

After mixing, the concrete was placed into cylindrical and prismatic molds and allowed to cure under wet burlap. After 3 days the molds were stripped and the concrete specimens were placed in a moist

cure room until required for testing. The entire curing process was done at room temperature.

Three sizes of specimens were cast for each mix. The size and shape of the specimens is easily determined from the code enscribed on the surface of each specimen. The letter of the code refers directly to the mix, either A, C or CX. The first number following the letter indicates the series which relates to the size and shape of the specimen in the following manner:

SERIES	SIZE	SHAPE	NO. OF REPLICATES PER MIX
1	76 mm ϕ x 152 mm	CYLINDER	1
3	152 mm ϕ x 305 mm	CYLINDER	11
4	76 mm x 101 mm x 406 mm	PRISM	12

The remaining number(s) of the code refer to the particular specimen. Steel reinforcing was placed in specimens 1 through 8 for series 3 of each mix. Each steel reinforcing bar was sandblasted, drilled, and tapped at the exposed end. Each bar was then placed into the centre of a freshly cast cylinder with 250 mm in the concrete and 54 mm exposed. See Figure 1 for details.

In addition, three copper/constantan Type T thermocouples were cast into specimens A45 and A38. The thermocouples were positioned to measure the overall temperature change of the specimen. The exact position of the thermocouples is illustrated in Figure 2. Difficulties encountered in removing specimen A38 from the mold resulted in the loss of the outermost thermocouple.

The above can now be separated into two equations:

$$R'' + \frac{1}{r} R' + \lambda^2 R = 0 \quad \dots 3$$

and

$$H'' + \lambda^2 H = 0 \quad \dots 4$$

3 can be solved using the boundary conditions ...

$$R(1) = 0 \quad \dots 3a$$

$$R'(0) = 0 \quad \dots 3b$$

Rearranging 3 yields:

$$rR'' + R' + \lambda^2 rR = 0 \quad \dots 5$$

which is a Sturm-Liouville boundary value problem, therefore we have orthogonal functions.

The general solution to 5 :

$$R = A J_0(\lambda r) + B Y_0(\lambda r)$$

where A and B are constants,

J_0 is a Bessel function of order zero and

Y_0 is a Bessel function of the second kind of order 0.

Now

$$R' = A \frac{d}{dr} [J_0(\lambda r)] + B \frac{d}{dr} [Y_0(\lambda r)]$$

$$R' = \lambda [A J_0'(\lambda r) + B Y_0'(\lambda r)]$$

$$R' = -\lambda [A J_1(\lambda r) + B Y_1(\lambda r)]$$

Applying the boundary condition 3b

that is $R'(0) = 0$

$$\therefore 0 = -\lambda [A J_1(0) + B Y_1(0)]$$

Now, limit $Y_1(x) = -\infty$

$$x \rightarrow 0$$

and, $J_1(0) = 0$

Since, $\lambda \neq 0$

then $B = 0$

Thus, $R = A \text{Jo}(\lambda r)$

Apply the boundary condition 3a

that is $R(1) = 0$

$$\therefore 0 = A \text{Jo}(\lambda)$$

Now, $A \neq 0$ (otherwise the trivial solution is obtained)

$$\therefore \text{Jo}(\lambda) = 0 \rightarrow \text{eigencondition}$$

$$\text{or } \text{Jo}(\lambda_n) = 0 \rightarrow \text{eigencondition}$$

and λ_n are the eigenvalues, $n \in \mathbb{N}$

Next, the general solution to 4 is obtained

$$H + \lambda^2 H = 0$$

... 4

General solution:

$$H = F e^{-\lambda^2 \theta}$$

where, F is a constant

Since $C = R \cdot H$, the two solutions are combined as ...

$$C = A_n \text{Jo}(\lambda_n r) \cdot F_n e^{-\lambda_n^2 \theta}$$

Now all solutions are combined as a series

$$C = \sum_{n=1}^{\infty} K_n \text{Jo}(\lambda_n r) e^{-\lambda_n^2 \theta}$$

where, $K_n = A_n \cdot F_n$

The final boundary condition, $C(r, 0) = 1$, is applied:

$$1 = \sum_{n=1}^{\infty} K_n \text{Jo}(\lambda_n r) e^0$$

$$1 = \sum_{n=1}^{\infty} K_n \text{Jo}(\lambda_n r)$$

The above is now multiplied by $r J_0(\lambda_m r)$, and integrated over $[0,1]$; $m \in \mathbb{N}$

$$\int_0^1 r J_0(\lambda_m r) dr = \sum_{n=1}^{\infty} K_n \int_0^1 r J_0(\lambda_n r) \cdot J_0(\lambda_m r) dr$$

Since we have orthogonal functions, all solutions with $n \neq m$ are 0.

$$\therefore n = m$$

and,

$$\int_0^1 r J_0(\lambda_n r) dr = K_n \int_0^1 r J_0^2(\lambda_n r) dr$$

$$\int_0^1 (\lambda_n r) J_0(\lambda_n r) d(\lambda_n r) = K_n \int_0^1 (\lambda_n r) J_0^2(\lambda_n r) d(\lambda_n r)$$

$$\lambda_n J_1(\lambda_n) = K_n \frac{\lambda_n^2}{2} [J_0^2(\lambda_n) + J_1^2(\lambda_n)]$$

but from the eigencondition,

$$J_0(\lambda_n) = 0$$

$$\therefore \lambda_n J_1(\lambda_n) = \frac{K_n \lambda_n^2}{2} J_1^2(\lambda_n)$$

thus,

$$K_n = 2 / \lambda_n J_1(\lambda_n)$$

Thus, the particular solution becomes ...

$$C = \sum_{n=1}^{\infty} \frac{2}{\lambda_n J_1(\lambda_n)} J_0(\lambda_n r) e^{-\lambda_n^2 \bar{\theta}}$$

Rearranging and re-introducing bars yields

$$\bar{C} = 2 \sum_{n=1}^{\infty} \frac{J_0(\lambda_n \bar{r})}{\lambda_n J_1(\lambda_n)} e^{-\lambda_n^2 \bar{\theta} / r_0^2}$$

The concentration variable has been normalized to vary from 1 to 0 which could be construed as a decreasing concentration. However,

it is equally correct mathematically to take the concentration increasing from 1 to 0. Physically, such a situation appears to be an apparent anomaly, but can be easily corrected for by inverting the final results.

That is ...

$$\bar{C} = 1 - 2 \sum_{n=1}^{\infty} \frac{J_0(\lambda_n \bar{r})}{\lambda_n J_1(\lambda_n)} e^{-\lambda_n^2 D / r_0^2}$$

where $\bar{C}$ is now defined as

$$\bar{C} = 1 - \frac{C - C_{\infty}}{C_i - C_{\infty}}$$

or

$$\bar{C} = \frac{C_i - C}{C_i - C_{\infty}} .$$

APPENDIX III

DATA FROM PRELIMINARY EXPERIMENT

TABLE 1: Measured Weight Change of Specimens

Wt. Change (g) between May 27 and June 6

<u>Specimen</u>	<u>Mix A</u>	<u>Mix C</u>	<u>Mix Cx</u>
11	-.2025	- .7462	-1.8212
12	+.0182	- .8192	-1.7389
21	-.0841	- .9208	-1.5297
22	-.0619	-1.2535	-2.0897
31	-.0959	- .0692	- .2891
32	-.0274	- .5736	- .5469
41	-.3829	- .9779	- .5581
42	-.1120	-1.0200	- .2600
51	+.1671	- .5206	- .8470
52	-.4490	- .7255	- .6575
61	-.4526	- .2875	- .2898
62	-.5019	- .0693	- .3754
71	-.2100	- .7716	-1.4233
72	-.3759	- .7959	-1.7539
81	-.7193	- .3469	- .2428
82	-.4247	- .8144	- .2238
91	-.3261	- .4431	- .7608
92	-.2518	- .4743	- .5725
101	-.3473	- .7128	- .6358
102	-.3595	- .6712	- .7028
111	-.6918	- .6496	- .6683
112	-1.0749	- .7114	- .7736
121	-.4367	- .3603	- .3126
122	-.4247	- .4673	- .3545
131	-.0158	+ .0858	-1.2046
132	+.0237	+ .1360	- .1403
141	-.8208	- .1733	- .4857
142	-.6999	- .1593	- .4573
151	+.0318	+ .0748	- .3942
152	+.1594	+ .2260	- .3093
161	-.2281	- .3844	- .5070
162	-.2927	- .4152	- .4923

+ indicates weight gain between May 27 and June 6

- indicates weight loss between May 27 and June 6

TABLE 1
APPENDIX IV*
DATA FROM ACCELERATED DURABILITY EXPERIMENT
WEIGHT IN AIR - PRISMS

SPECIMEN	WEIGHT IN AIR, grams			% Change compared to Original	
	0 Cycles	27 Cycles	53 Cycles	27 Cycles	53 Cycles
A43	7236	7211	7197	-0.3	-0.5
A44	7322	7301	7289	-0.3	-0.5
A49	7220	7175	7151	-0.6	-1.0
A410	7240	7199	7177	-0.6	-0.9
Ave.	7255	7222	7204	-0.5	-0.7
C43	7313	7251	7226	-0.8	-1.2
C44	7174	7105	7068	-1.0	-1.5
C49	7365	7283	7251	-1.1	-1.5
C410	7269	7185	7152	-1.2	-1.6
Ave.	7280	7206	7174	-1.0	-1.5
CX43	7125	7133	7135	0.1	0.1
CX44	7165	7174	7177	0.1	0.2
CX49	7264	7273	7291	0.1	0.2
CX410	7212	7226	7232	0.2	0.3
Ave.	7192	7207	7206	0.1	0.2
CONTROLS					
A42	7220	7221	7223	0.0	0.0
A411	7290	7293	7294	0.0	0.1
A412	7402	7403	7399	0.0	0.0
Ave.	7304	7306	7305	0.0	0.0
C45	7281	7285	7283	0.1	0.0
C411	7357	7357	7355	0.0	0.0
C412	7349	7353	7349	0.1	0.0
Ave.	7329	7332	7329	0.1	0.0
CX45	7241	7243	7244	0.0	0.0
CX411	7211	7214	7213	0.0	0.0
CX412	7158	7158	7152	0.0	-0.1
Ave.	7203	7205	7203	0.0	0.0

* Where a dash "-" occurs in the data it indicates either that readings could not be taken or that the readings were obviously in error.

TABLE 1 - cont'd

DATA

WEIGHT IN AIR - PRISMS

SPECIMENS	WEIGHT IN AIR (grams)			% Change compared to Original		
	119 cycles	204 cycles	265 cycles	119 cycles	204 cycles	265 cycles
A43	7174	7122	7130	-1.2	-1.6	-1.5
A44	7242	7211	7229	-1.1	-1.5	-1.3
A49	7090	7047	7062	-1.8	-2.4	-2.2
A410	7097	7047	7075	-2.0	-2.7	-2.3
Ave.	7144	7107	7124	-1.5	-2.0	-1.8
C43	7138	7095	7131	-2.4	-3.0	-2.5
C44	6986	6932	6965	-2.6	-3.4	-2.9
C49	7175	7139	7209	-2.6	-3.1	-2.1
C410	7068	7038	7122	-2.8	-3.2	-2.0
Ave.	7092	7051	7107	-2.6	-3.1	-2.4
CX43	7104	7078	7129	-0.3	-0.7	0.1
CX44	7154	7132	7172	-0.2	-0.5	0.1
CX49	7269	7264	7338	0.1	0.0	1.0
CX410	7217	7205	7256	0.1	-0.1	0.6
Ave.	7186	7170	7224	-0.1	-0.3	0.4
CONTROLS						
A42	7224	7217	7225	0.1	0.0	0.1
A411	7288	7281	7297	0.0	-0.1	0.1
A412	7400	7394	7403	0.0	-0.1	0.0
Ave.	7304	7297	7308	0.0	-0.1	0.1
C45	7284	7269	7282	0.0	-0.2	0.0
C411	7356	7333	7354	0.0	-0.3	0.0
C412	7348	7238	7348	0.0	-1.5	0.0
Ave.	7329	7280	7328	0.0	-0.7	0.0
CX45	7244	7234	7239	0.0	-0.1	0.0
CX411	7210	7202	7211	0.0	-0.1	0.0
CX412	7156	7141	7157	0.0	-0.2	0.0
Ave.	7203	7192	7202	0.0	-0.2	0.0

TABLE 1 - cont'd

DATA

WEIGHT IN AIR - PRISMS

SPECIMEN	WEIGHT IN AIR (g)		% Change compared to Original	
	335 cycles	427 cycles	335 cycles	427 cycles
A43	7103	7068	-1.8	-2.3
A44	7205	7168	-1.6	-2.1
A49	7034	6997	-2.6	-3.1
A410	7045	7010	-2.7	-3.2
Ave.	7097	7061	-2.2	-2.7
C43	7095	7065	-3.0	-3.4
C44	6941	6907	-3.2	-3.7
C49	7166	7153	-2.7	-2.9
C410	7083	7064	-2.6	-2.8
Ave.	7077	7047	-2.9	-3.2
CX43	7119	7091	-0.1	-0.5
CX44	7140	7118	-0.3	-0.7
CX49	7320	7343	0.8	1.1
CX410	7251	7227	0.5	0.2
Ave.	7208	7195	0.2	0.0
CONTROLS				
A42	7231	7232	0.2	0.2
A411	7296	7299	0.1	0.1
A412	7411	7405	0.1	0.0
Ave.	7313	7312	0.1	0.1
C45	7287	7285	0.1	0.1
C411	7362	7359	0.1	0.0
C412	7350	7352	0.0	0.1
Ave.	7333	7332	0.1	0.0
CX45	7251	7251	0.1	0.1
CX411	7221	7220	0.1	0.1
CX412	7158	7162	0.0	0.1
Ave.	7210	7211	0.1	0.1

TABLE 1 - con't

DATA

WEIGHT IN AIR - PRISMS

SPECIMEN	WEIGHT IN AIR (g)			%CHANGE COMPARED TO ORIGINAL		
	550 cycles	658 cycles	734 cycles	550 cycles	658 cycles	734 cycles
A43	7021	6988	6985	-3.0	-3.6	-3.5
A44	-	-	-	-	-	-
A49	7045	7039	7028	-2.4	-2.5	-2.7
A410	6963	6974	6968	-3.8	-3.7	-3.8
Ave.	<u>7010</u>	<u>7000</u>	<u>6994</u>	<u>-3.1</u>	<u>-3.3</u>	<u>-3.3</u>
C43	7031	7049	7055	-3.8	-3.6	-3.5
C44	6997	6978	6985	-2.4	-2.7	-2.6
C49	7249	7208	7206	-1.5	-2.1	-2.2
C410	7075	7083	7065	-2.5	-2.6	-2.8
Ave.	<u>7088</u>	<u>7080</u>	<u>7078</u>	<u>-2.6</u>	<u>-2.8</u>	<u>-2.8</u>
CX43	7056	7057	7028	-0.9	-1.0	-1.4
CX44	-	-	-	-	-	-
CX49	-	-	-	-	-	-
CX410	7254	7257	7229	0.1	0.6	0.2
Ave.	<u>7155</u>	<u>7157</u>	<u>7129</u>	<u>-0.4</u>	<u>-0.2</u>	<u>-0.6</u>
CONTROLS						
A42	7238	7247	7247	0.3	0.4	0.4
A411	7300	7313	7311	0.2	0.3	0.3
A412	7412	7421	7423	0.2	0.3	0.3
Ave.	<u>7317</u>	<u>7327</u>	<u>7327</u>	<u>0.2</u>	<u>0.3</u>	<u>0.3</u>
C45	7287	7299	7302	0.1	1.0	1.0
C411	7360	7369	7371	0.2	0.2	0.2
C412	7349	7364	7364	0.2	0.2	0.2
Ave.	<u>7332</u>	<u>7344</u>	<u>7346</u>	<u>0.2</u>	<u>0.5</u>	<u>0.5</u>
CX45	7250	7259	7262	0.2	0.3	0.3
CX411	7220	7232	7230	0.2	0.3	0.3
CX412	7165	7174	7175	0.2	0.2	0.2
Ave.	<u>7212</u>	<u>7222</u>	<u>7222</u>	<u>0.2</u>	<u>0.3</u>	<u>0.3</u>

TABLE 1 - con't

DATA

WEIGHT IN AIR - PRISMS

SPECIMEN	WEIGHT IN AIR (g)		%CHANGE COMPARED TO ORIGINAL	
	828 cycles	975 cycles	828 cycles	975 cycles
A43	6976	6971	-3.6	-3.7
A44	-	-	-	-
A49	7040	7013	-2.5	-2.9
A410	6962	6963	-3.8	-3.8
Ave.	6993	6982	-3.3	-3.5
C43	7051	7049	-3.6	-3.6
C44	6973	6994	-2.8	-2.5
C49	7197	7187	-2.3	-2.4
C410	7480	7069	-	-2.8
Ave.	7175	7075	-2.9	-2.8
CX43	7052	7017	-1.0	-1.5
CX44	-	-	-	-
CX49	-	-	-	-
CX410	7214	7189	0.0	-0.3
Ave.	7133	7103	-0.5	-0.9
CONTROLS				
A42	7255	7252	0.7	0.4
A411	7322	7317	0.6	0.4
A412	7427	7429	0.5	0.4
Ave.	7335	7333	0.6	0.4
C45	7303	7308	0.2	1.1
C411	7376	7379	0.3	0.3
C412	7368	7372	0.5	0.3
Ave.	7349	7353	0.3	0.6
CX45	7266	7265	0.5	0.3
CX411	7234	7235	0.4	0.3
CX412	7173	7180	0.3	0.3
Ave.	7224	7227	0.4	0.3

TABLE 2

DATA

WEIGHT UNDER WATER - PRISMS

SPECIMENS	WEIGHT UNDER WATER (grams)			% Change compared to Original	
	0 cycles	27 cycles	53 cycles	27 cycles	53 cycles
A43	4115	4096	4082	-0.5	-0.8
A44	4181	4166	4156	-0.4	-0.6
A49	4079	4033	4013	-1.1	-1.6
A410	4100	4066	4042	-0.9	-1.4
Ave.	4119	4090	4073	-0.7	-1.1
C43	4151	4097	4076	-1.3	-1.8
C44	4052	3990	3957	-1.5	-2.3
C49	4225	4145	4115	-1.9	-2.6
C410	4123	4045	4017	-1.9	-2.6
Ave.	4138	4069	4041	-1.7	-2.3
CX43	4012	4023	4028	0.3	0.4
CX44	4037	4053	4061	0.4	0.6
CX49	4133	4143	4151	0.2	0.4
CX410	4077	4092	4101	0.4	0.6
Ave.	4065	4077	4085	0.3	0.5
CONTROLS					
A42	4102	4108	4110	0.1	0.2
A411	4142	4143	4147	0.1	0.1
A412	4217	4222	4219	0.1	0.0
Ave.	4154	4158	4159	0.1	0.1
C45	4167	4163	4164	-0.1	-0.1
C411	4199	4201	4200	0.0	0.0
C412	4202	4207	4207	0.1	0.1
Ave.	4189	4190	4190	0.0	0.0
CX45	4093	4096	4097	0.1	0.1
CX411	4081	4085	4085	0.1	0.1
CX412	4039	4036	4032	-0.1	-0.2
Ave.	4071	4072	4071	0.0	0.0

TABLE 2 - cont'd

DATA

WEIGHT UNDER WATER - PRISMS

SPECIMENS	WEIGHT UNDER WATER (grams)			% Change Compared to Original		
	119 cycles	204 cycles	265 cycles	119 cycles	204 cycles	265 cycles
A43	4032	4008	4012	-2.0	-2.6	-2.5
A44	4107	4084	4087	-1.8	-2.3	-2.2
A49	3950	3913	3922	-3.2	-4.1	-3.8
A410	3965	3924	3938	-3.3	-4.3	-4.0
Ave.	4014	3982	3990	-2.5	-3.3	-3.1
C43	3988	3956	3971	-3.9	-4.7	-4.3
C44	3871	3832	3845	-4.5	-5.4	-5.1
C49	4036	4005	4066	-4.5	-5.2	-3.8
C410	3933	3907	3978	-4.6	-5.2	-3.5
Ave.	3957	3925	3965	-4.4	-5.1	-4.2
CX43	3999	3983	4016	-0.3	-0.7	0.1
CX44	4034	4022	4047	-0.1	-0.4	0.2
CX49	4141	4135	4192	0.2	0.0	1.4
CX410	4086	4018	4118	0.2	-1.4	1.0
Ave.	4065	4040	4093	0.0	-0.6	0.7
CONTROLS						
A42	4110	4102	4104	0.2	0.0	0.0
A411	4143	4144	4144	0.0	0.0	0.0
A412	4222	4220	4219	0.1	0.1	0.0
Ave.	4158	4155	4156	0.1	0.0	0.0
C45	4157	4152	4152	-0.2	-0.4	-0.4
C411	4198	4179	4194	0.0	-0.5	-0.1
C412	4203	4197	4199	0.0	-0.1	-0.1
Ave.	4186	4176	4182	-0.1	-0.3	-0.2
CX45	4096	4087	4083	0.1	-0.1	-0.2
CX411	4077	4074	4077	-0.1	-0.2	-0.1
CX412	4033	4020	4028	-0.1	-0.5	-0.3
Ave.	4069	4060	4063	0.0	-0.3	-0.2

TABLE 2 - cont'd

DATA

WEIGHT UNDER WATER - PRISMS

SPECIMEN	WEIGHT UNDER WATER (g)		% Change Compared to Original	
	335 cycles	427 cycles	335 cycles	427 cycles
A43	3988	3950	-3.1	-4.0
A44	4069	4033	-2.7	-3.5
A49	3892	3856	-4.6	-5.5
A410	3911	3875	-4.6	-5.5
Ave.	3965	3929	-3.7	-4.6
C43	3940	3910	-5.1	-5.8
C44	3823	3791	-5.7	-6.4
C49	4027	4014	-4.7	-5.0
C410	3941	3922	-4.4	-4.9
Ave.	3933	3909	-5.0	-5.5
CX43	4007	3980	-0.1	-0.8
CX44	4024	4005	-0.3	-0.8
CX49	4177	4199	1.1	1.6
CX410	4110	4092	0.8	0.4
Ave.	4080	4069	0.4	0.1
CONTROLS				
A42	4117	4117	0.4	0.4
A411	4148	4152	0.1	0.2
A412	4229	4223	0.3	0.1
Ave.	4165	4164	0.3	0.2
C45	4161	4160	-0.1	-0.2
C411	4202	4200	0.1	0.0
C412	4203	4205	0.0	0.1
Ave.	4189	4188	0.0	0.0
CX45	4102	4102	0.2	0.2
CX411	4089	4088	0.2	0.2
CX412	4033	4037	-0.1	0.0
Ave.	4075	4076	0.1	0.1

TABLE 2 - con't

DATA

WEIGHT UNDER WATER - PRISMS

SPECIMEN	WEIGHT UNDER WATER (g)			%CHANGE COMPARED TO ORIGINAL		
	550 cycles	658 cycles	734 cycles	550 cycles	658 cycles	734 cycles
A43	3902	3864	3865	-5.2	-6.1	-6.1
A44	-	-	-	-	-	-
A49	3902	3892	3884	-4.3	-4.6	-4.8
A410	3824	3834	3833	-6.7	-6.5	-6.5
Ave.	<u>3876</u>	<u>3863</u>	<u>3861</u>	<u>-5.4</u>	<u>-5.7</u>	<u>-5.8</u>
C43	3874	3884	3893	-6.7	-6.4	-6.2
C44	3879	3848	3857	-4.3	-5.0	-4.8
C49	4105	4063	4066	-2.8	-3.8	-3.8
C410	3941	3933	3923	-4.4	-4.6	-4.9
Ave.	<u>3950</u>	<u>3932</u>	<u>3935</u>	<u>-4.6</u>	<u>-5.0</u>	<u>-4.9</u>
CX43	3944	3938	3915	-1.7	-1.8	-2.4
CX44	-	-	-	-	-	-
CX49	-	-	-	-	-	-
CX410	4129	4112	4092	1.3	0.9	0.4
Ave.	<u>4037</u>	<u>4025</u>	<u>4004</u>	<u>-0.2</u>	<u>-0.5</u>	<u>-1.0</u>
CONTROLS						
A42	4120	4127	4128	0.4	0.6	0.6
A411	4153	4160	4167	0.3	0.4	0.6
A412	4229	4234	4238	0.3	0.4	0.5
Ave.	<u>4167</u>	<u>4174</u>	<u>4178</u>	<u>0.3</u>	<u>0.5</u>	<u>0.6</u>
C45	4172	4168	4172	0.1	0.0	0.1
C411	4222	4207	4211	0.1	0.2	0.3
C412	4211	4211	4217	0.2	0.2	0.4
Ave.	<u>4202</u>	<u>4195</u>	<u>4200</u>	<u>0.1</u>	<u>0.1</u>	<u>0.3</u>
CX45	4101	4105	4111	0.2	0.3	0.4
CX411	4092	4095	4097	0.3	0.3	0.4
CX412	4043	4046	4049	0.1	0.2	0.2
Ave.	<u>4079</u>	<u>4082</u>	<u>4086</u>	<u>0.2</u>	<u>0.3</u>	<u>0.3</u>

TABLE 2 - con't

DATA

WEIGHT UNDER WATER - PRISMS

SPECIMEN	WEIGHT UNDER WATER (g)		%CHANGE COMPARED TO ORIGINAL	
	828 cycles	975 cycles	828 cycles	975 cycles
A43	3839	3844	-6.2	-6.6
A44	-	-	-	-
A49	3887	3855	-4.7	-5.5
A410	3822	3818	-6.8	-6.9
Ave.	3849	3839	-5.9	-6.3
C43	3899	3885	-6.1	-6.4
C44	3848	3869	-5.0	-4.5
C49	4053	4032	-4.1	-4.6
C410	3936	3919	-4.5	-5.0
Ave.	3936	3926	-4.9	-5.1
CX43	3936	3916	-1.9	-2.4
CX44	-	-	-	-
CX49	-	-	-	-
CX410	4098	4069	0.5	-0.2
Ave.	4017	3993	-0.7	-1.3
CONTROLS				
A42	4131	4129	0.7	0.7
A411	4167	4167	0.6	0.6
A412	4239	4237	0.5	0.5
Ave.	4179	4178	0.6	0.6
C45	4174	4173	0.2	0.1
C411	4213	4206	0.3	0.2
C412	4224	4216	0.5	0.3
Ave.	4204	4198	0.3	0.2
CX45	4113	4110	0.5	0.4
CX411	4099	4095	0.4	0.3
CX412	4049	4045	0.3	0.2
Ave.	4087	4083	0.4	0.3

TABLE 3

DATA

VOLUMES OF PRISMS

SPECIMENS	VOLUME (cm ³)			% Change compared to original	
	0 cycles	27 cycles	53 cycles	27 cycles	53 cycles
A43	3124	3118	3118	-0.19	-0.19
A44	3144	3138	3148	-0.19	-0.13
A49	3144	3145	3141	0.03	-0.13
A410	3143	3137	3138	-0.19	-0.16
Ave.	3139	3135	3136	-0.13	-0.10
C43	3165	3157	3153	-0.25	-0.38
C44	3125	3118	3114	-0.22	-0.35
C49	3143	3141	3139	-0.06	-0.13
C410	3149	3143	3138	-0.19	-0.35
Ave.	3146	3140	3136	-0.19	-0.32
CX43	3116	3113	3110	-0.10	-0.19
CX44	3131	3124	3119	-0.22	-0.38
CX49	3134	3133	3133	-0.03	-0.03
CX410	3138	3137	3134	-0.03	-0.13
Ave.	3130	3127	3127	-0.10	-0.10
CONTROLS					
A42	3121	3116	3116	-0.16	-0.16
A411	3151	3151	3151	0.00	0.00
A412	3188	3184	3184	-0.13	-0.13
Ave.	3153	3150	3150	-0.10	-0.10
C45	3117	3125	3125	0.26	0.26
C411	3161	3159	3159	-0.06	-0.06
C412	3150	3149	3149	-0.03	-0.03
Ave.	3143	3144	3144	-0.03	-0.03
CX45	3151	3150	3150	-0.03	-0.03
CX411	3133	3132	3132	-0.03	-0.03
CX412	3122	3125	3125	0.10	0.10
Ave.	3135	3136	3136	0.03	0.03

TABLE 3 - cont'd

DATA

VOLUMES OF PRISMS

SPECIMENS	VOLUME (cm ³)			% Change compared to original		
	119 cycles	204 cycles	265 cycles	119 cycles	204 cycles	265 cycles
A43	3118	3117	3119	-0.19	-0.22	-0.16
A44	3138	3130	3143	-0.19	-0.45	-0.03
A49	3143	3137	3141	-0.03	-0.22	-0.10
A410	3135	3126	3138	-0.25	-0.54	-0.16
Ave.	3134	3126	3136	-0.16	-0.41	-0.10
C43	3153	3142	3161	-0.38	-0.73	-0.13
C44	3118	3103	3121	-0.22	-0.70	-0.13
C49	3142	3137	3144	-0.03	-0.19	0.03
C410	3138	3134	3145	-0.35	-0.48	-0.13
Ave.	3138	3129	3144	-0.25	-0.54	-0.06
CX43	3108	3098	3114	-0.26	-0.58	-0.06
CX44	3123	3113	3126	-0.26	-0.57	-0.16
CX49	3131	3132	3147	-0.10	-0.06	0.41
CX410	3134	3190	3139	-0.13	1.66	0.03
Ave.	3124	3133	3132	-0.19	0.10	0.05
CONTROLS						
A42	3117	3118	3122	-0.13	-0.10	0.03
A411	3148	3140	3154	-0.10	-0.35	0.10
A412	3181	3177	3185	-0.22	-0.35	-0.35
Ave.	3149	3145	3155	-0.13	-0.25	0.06
C45	3130	3120	3131	0.42	0.10	0.45
C411	3161	3157	3161	0.00	-0.13	0.00
C412	3148	-	3150	-0.06	-	0.00
Ave.	3146	3138	3148	0.16	-0.02	0.16
CX45	3151	3150	3157	0.00	-0.03	0.19
CX411	3136	3131	3135	0.10	-0.06	0.06
CX412	3126	3124	3130	0.13	0.06	0.26
Ave.	3138	3135	3142	0.10	0.00	0.22

TABLE 3 - cont'd

DATA

VOLUMES OF PRISMS

SPECIMEN	VOLUME (cm ³)		% Change compared to original	
	335 cycles	427 cycles	335 cycles	427 cycles
A43	3116	3122	-0.26	-0.06
A44	3137	3140	-0.22	-0.13
A49	3143	3146	-0.03	0.06
A410	3135	3140	-0.25	-0.10
Ave.	3134	3137	-0.16	-0.06
C43	3156	3160	-0.28	-0.16
C44	3119	3120	-0.19	-0.16
C49	3140	3144	-0.10	0.03
C410	3143	3147	-0.19	-0.06
Ave.	3140	3143	-0.19	-0.10
CX43	3113	3115	-0.10	-0.03
CX44	3117	3117	-0.45	-0.45
CX49	3144	3149	0.32	0.48
CX410	3142	3140	0.13	0.06
Ave.	3130	3131	0.00	0.03
CONTROLS				
A42	3117	3119	-0.13	-0.06
A411	3151	3152	0.00	0.03
A412	3185	3187	-0.09	-0.03
Ave.	3151	3153	-0.06	0.00
C45	3129	3130	0.38	0.42
C411	3163	3164	0.06	0.09
C412	3150	3149	0.00	-0.03
Ave.	3147	3149	0.13	0.19
CX45	3152	3154	0.03	0.10
CX411	3135	3137	0.06	0.13
CX412	3128	3130	0.19	0.26
Ave.	3138	3140	0.10	0.16

TABLE 3 - con't

DATA

VOLUME - PRISMS

SPECIMEN	VOLUME (cm ³)			%CHANGE COMPARED TO ORIGINAL		
	550 cycles	658 cycles	734 cycles	550 cycles	658 cycles	734 cycles
A43	3126	3128	3128	0.1	0.1	0.1
A44	-	-	-	-	-	-
A49	3152	3151	3167	0.3	0.2	0.7
A410	3145	3209	3143	0.1	2.1	0.0
Ave.	3141	3163	3146	0.2	0.8	0.3
C43	3168	3169	3170	0.2	0.1	0.2
C44	3133	3134	3136	0.3	0.3	0.4
C49	3154	3149	3148	0.4	0.2	0.2
C410	3153	3154	3150	0.0	0.2	0.0
Ave.	3152	3152	3151	0.2	0.2	0.2
CX43	3125	3123	3121	0.3	0.2	0.2
CX44	-	-	-	-	-	-
CX49	-	-	-	-	-	-
CX410	3149	3149	3145	0.4	0.4	0.2
Ave.	3138	3136	3133	0.4	0.3	0.2
CONTROLS						
A42	3127	3124	3127	0.2	0.1	0.2
A411	3158	3157	3152	0.2	0.2	0.0
A412	3193	3191	3193	0.2	0.1	0.2
Ave.	3159	3157	3157	0.2	0.1	0.1
C45	3135	3135	3138	0.6	0.6	0.7
C411	3153	3166	3168	-0.3	0.2	0.2
C412	3158	3157	3155	0.3	0.2	0.2
Ave.	3149	3153	3154	0.2	0.3	0.4
CX45	3159	3158	3159	0.3	0.2	0.3
CX411	3140	3168	3141	0.2	1.1	0.3
CX412	3134	3132	3134	0.4	0.3	0.4
Ave.	3144	3153	3145	0.3	0.5	0.3

TABLE 3 - con't

DATA

VOLUME - PRISMS

SPECIMEN	VOLUME (cm ³)		%CHANGE COMPARED TO ORIGINAL	
	828 cycles	975 cycles	828 cycles	975 cycles
A43	3128	3135	0.1	0.3
A44	-	-	-	-
A49	3164	3166	0.6	0.7
A410	3151	3153	0.3	0.3
Ave.	3148	3151	0.3	0.5
C43	3163	3172	-0.1	0.2
C44	3136	3166	0.4	0.3
C49	3155	3163	0.4	0.6
C410	-	3158	-	0.3
Ave.	3151	3156	0.2	0.4
CX43	3127	3109	0.4	-0.2
CX44	-	-	-	-
CX49	-	-	-	-
CX410	3127	3128	-0.4	-0.3
Ave.	3127	3118	0.0	-0.3
CONTROLS				
A42	3135	3131	0.5	0.3
A411	3166	3158	0.5	0.2
A412	3199	3200	0.4	0.4
Ave.	3167	3163	0.4	0.3
C45	3140	3137	0.7	0.8
C411	3174	3181	0.4	0.6
C412	3155	3164	0.2	0.4
Ave.	3156	3162	0.4	0.6
CX45	3164	3163	0.4	0.4
CX411	3146	3148	0.4	0.5
CX412	3134	3143	0.4	0.7
Ave.	3149	3151	0.4	0.5

TABLE 4

DATA

DENSITY MEASUREMENTS - PRISMS

SPECIMEN	DENSITY MEASUREMENT, kg/m ³			%Change compared to original	
	0 cycles	27 cycles	53 cycles	27 cycles	53 cycles
A43	2316	2312	2308	-0.2	-0.3
A44	2328	2326	2324	-0.1	-0.2
A49	2296	2281	2277	-0.7	-0.8
A410	2303	2294	2287	-0.4	-0.7
Ave.	2311	2303	2299	-0.4	-0.5
C43	2310	2296	2292	-0.6	-0.8
C44	2295	2278	2270	-0.7	-1.1
C49	2343	2318	2310	-1.1	-1.4
C410	2308	2285	2279	-1.0	-1.3
Ave.	2314	2294	2288	-0.9	-1.1
CX43	2286	2291	2294	0.2	0.3
CX44	2288	2296	2301	0.3	0.6
CX49	2317	2319	2324	0.1	0.3
CX410	2298	2303	2307	0.2	0.4
Ave.	2297	2302	2307	0.2	0.4
CONTROLS					
A42	2313	2317	2318	0.2	0.2
A411	2313	2314	2315	0.0	0.1
A412	2321	2324	2324	0.1	0.1
Ave.	2316	2318	2319	0.1	0.1
C45	2335	2331	2333	-0.2	-0.1
C411	2327	2328	2329	0.0	0.1
C412	2332	2334	2337	0.1	0.2
Ave.	2331	2331	2333	0.0	0.1
CX45	2297	2299	2300	0.1	0.1
CX411	2301	2303	2304	0.1	0.1
CX412	2292	2290	2290	-0.1	-0.1
Ave.	2297	2297	2298	0.0	0.0

TABLE 4 - cont'd

DATA

DENSITY MEASUREMENTS - PRISMS

SPECIMEN	DENSITY (kg/m ³)			% Change compared to original		
	119 cycles	204 cycles	265 cycles	119 cycles	204 cycles	265 cycles
A43	2292	2285	2285	-1.0	-1.3	-1.3
A44	2307	2304	2299	-0.9	-1.0	-1.2
A49	2255	2246	2247	-1.8	-2.2	-2.1
A410	2263	2254	2253	-1.7	-2.1	-2.1
Ave.	2280	2272	2272	-1.3	-1.7	-1.7
C43	2263	2258	2255	-2.0	-2.3	-2.4
C44	2240	2234	2231	-2.4	-2.7	-2.8
C49	2283	2276	2292	-2.6	-2.9	-2.2
C410	2252	2246	2263	-2.4	-2.7	-1.9
Ave.	2260	2253	2261	-2.3	-2.6	-2.3
CX43	2285	2285	2288	0.0	0.0	0.1
CX44	2290	2291	2293	0.1	0.1	0.2
CX49	2321	2319	2331	0.2	0.1	0.6
CX410	2302	2258	2310	0.2	-1.7	0.5
Ave.	2300	2288	2306	0.1	-0.4	0.4
CONTROLS						
A42	2317	2315	2313	0.2	0.1	0.0
A411	2315	2319	2312	0.1	0.3	0.0
A412	2326	2327	2323	0.2	0.3	0.1
Ave.	2320	2320	2317	0.2	0.2	0.0
C45	2327	2330	2325	-1.2	-0.2	-0.4
C411	2326	2323	2325	0.0	-0.2	-0.1
C412	2334	2378	2332	0.1	2.0	0.0
Ave.	2329	2343	2328	-0.4	0.5	-0.1
CX45	2298	2296	2292	0.0	0.0	-0.2
CX411	2299	2300	2299	-0.1	0.0	-0.1
CX412	2289	2286	2293	-0.1	-0.3	0.0
Ave.	2297	2294	2293	0.0	-0.1	-0.2

TABLE 4 - cont'd

DATA

DENSITY MEASUREMENTS - PRISMS

SPECIMEN	DENSITY		% Change compared to original	
	335 cycles	427 cycles	335 cycles	427 cycles
A43	2278	2263	-1.6	-2.3
A44	2296	2282	-1.4	-2.0
A49	2237	2224	-2.6	-3.1
A410	2246	2232	-2.5	-3.1
Ave.	2265	2251	-2.0	-2.6
C43	2247	2235	-2.7	-3.2
C44	2224	2213	-3.1	-3.6
C49	2281	2275	-2.6	-2.9
C410	2252	2244	-2.4	-2.8
Ave.	2252	2242	-2.7	-3.1
CX43	2286	2275	0.0	-0.5
CX44	2290	2282	0.1	-0.3
CX49	2327	2331	0.4	0.6
CX410	2307	2301	0.4	0.1
Ave.	2303	2298	0.3	0.0
CONTROLS				
A42	2319	2317	0.3	0.2
A411	2315	2315	0.1	0.1
A412	2326	2323	0.2	0.1
Ave.	2321	2319	0.2	0.1
C45	2328	2327	-0.3	-0.3
C411	2327	2325	0.0	-0.1
C412	2333	2332	0.0	0.0
Ave.	2330	2329	0.0	-0.1
CX45	2300	2298	0.1	0.0
CX411	2303	2301	0.1	0.0
CX412	2288	2288	-0.2	-0.2
Ave.	2297	2296	0.0	0.0

TABLE 4 - con't

DATA

DENSITY - PRISMS

SPECIMEN	DENSITY (kg/m ³)			%CHANGE COMPARED TO ORIGINAL		
	550 cycles	658 cycles	734 cycles	550 cycles	658 cycles	734 cycles
A43	2246	2234	2223	-3.0	-3.5	-4.0
A44	-	-	-	-	-	-
A49	2236	2234	2230	-2.6	-2.7	-2.9
A410	2214	2173	2217	-3.9	-5.6	-3.7
Ave.	<u>2232</u>	<u>2214</u>	<u>2223</u>	<u>-3.2</u>	<u>-4.0</u>	<u>-3.5</u>
C43	2221	2224	2226	-3.9	-3.7	-3.6
C44	2236	2227	2228	-2.6	-3.0	-2.9
C49	2299	2289	2289	-4.1	-2.3	-2.3
C410	2248	2246	2243	-2.6	-2.7	-2.8
Ave.	<u>2251</u>	<u>2247</u>	<u>2247</u>	<u>-3.3</u>	<u>-2.9</u>	<u>-2.9</u>
CX43	2259	2260	2252	-1.2	-1.1	-1.5
CX44	-	-	-	-	-	-
CX49	-	-	-	-	-	-
CX410	2309	2305	2299	-0.5	0.3	0.0
Ave.	<u>2284</u>	<u>2283</u>	<u>2276</u>	<u>-0.9</u>	<u>-0.4</u>	<u>-0.8</u>
CONTROLS						
A42	2315	2320	2318	-0.1	0.3	0.2
A411	2313	2316	2320	0.0	0.1	0.3
A412	2322	2326	2325	0.0	0.2	0.2
Ave.	<u>2317</u>	<u>2321</u>	<u>2321</u>	<u>0.0</u>	<u>0.2</u>	<u>0.2</u>
C45	2329	2328	2327	-0.3	-0.3	-0.3
C411	2337	2328	2327	0.4	0.0	0.0
C412	2331	2333	2334	0.0	0.0	0.1
Ave.	<u>2332</u>	<u>2330</u>	<u>2329</u>	<u>0.0</u>	<u>-0.1</u>	<u>-0.1</u>
CX45	2296	2299	2299	0.0	0.1	0.1
CX411	2301	2283	2302	0.0	-0.8	0.0
CX412	2288	2291	2290	-0.2	0.0	-0.1
Ave.	<u>2295</u>	<u>2291</u>	<u>2297</u>	<u>-0.1</u>	<u>-0.2</u>	<u>0.0</u>

TABLE 4 - con't

DATA

DENSITY - PRISMS

SPECIMEN	DENSITY (kg/m ³)		%CHANGE COMPARED TO ORIGINAL	
	828 cycles	975 cycles	828 cycles	975 cycles
A43	2230	2224	-3.7	-4.0
A44	-	-	-	-
A49	2234	2215	-3.1	-3.5
A410	2214	2208	-4.1	-4.1
Ave.	2227	2216	-3.6	-3.9
C43	2226	2222	-3.5	-3.8
C44	2226	2209	-3.1	-2.7
C49	2282	2272	-2.6	-3.0
C410	-	2238	-	-3.0
Ave.	2245	2235	-3.1	-3.1
CX43	2257	2257	-1.3	-1.3
CX44	-	-	-	-
CX49	-	-	-	-
CX410	2291	2298	0.4	0.0
Ave.	2274	2278	-0.5	-0.7
CONTROLS				
A42	2320	2316	0.1	0.2
A411	2319	2317	0.0	0.2
A412	2326	2322	0.0	0.0
Ave.	2322	2218	0.0	0.1
C45	2330	2330	-0.4	-0.4
C411	2339	2320	-0.1	-0.3
C412	2333	2330	0.1	-0.1
Ave.	2334	2327	-0.1	-0.3
CX45	2300	2297	0.0	0.0
CX411	2304	2298	-0.1	-0.1
CX412	2289	2284	-0.2	-0.3
Ave.	2298	2293	-0.1	-0.1

TABLE 5

DATA

 ρ/t^2 - PRISMS

SPECIMENS	$\rho/t^2 \times 10^{-12}, \text{ kg/m}^3 \text{ sec}^3$					
	0 cycles	27 cycles	53 cycles	119 cycles	204 cycles	265 cycles
A43	0.292	0.290	0.277	0.273	0.271	0.256
A44	0.297	0.287	0.291	0.276	0.273	0.257
A49	0.278	0.265	0.265	0.258	0.256	0.235
A410	0.281	0.266	0.262	0.250	0.236	0.221
Ave.	0.287	0.274	0.273	0.264	0.258	0.241
C43	0.274	0.257	0.255	0.231	0.228	0.221
C44	0.264	0.243	0.243	0.224	0.219	0.206
C49	0.285	0.258	0.253	0.230	0.219	0.216
C410	0.268	0.251	0.246	0.234	0.225	0.276
Ave.	0.273	0.252	0.249	0.230	0.222	0.217
CX43	0.266	0.265	0.265	0.247	0.240	0.229
CX44	0.262	0.257	0.257	0.250	0.240	0.216
CX49	0.270	0.266	0.265	0.232	0.203	0.207
CX410	0.262	0.261	0.262	0.240	0.221	0.218
Ave.	0.265	0.262	0.262	0.242	0.225	0.217
CONTROLS						
A42	0.291	0.293	0.292	0.294	0.288	0.286
A411	0.284	0.292	0.290	0.287	0.289	0.274
A412	0.287	0.300	0.297	0.295	0.298	0.288
Ave.	0.287	0.295	0.293	0.293	0.298	0.283
C45	0.283	0.284	0.287	0.283	0.288	0.279
C411	0.278	0.287	0.292	0.285	0.270	0.277
C412	0.279	0.285	0.299	0.286	0.292	0.278
Ave.	0.279	0.285	0.286	0.285	0.283	0.278
CX45	0.268	0.278	0.278	0.278	0.277	0.273
CX411	0.268	0.270	0.275	0.272	0.275	0.265
CX412	0.267	0.267	0.269	0.271	0.265	0.265
Ave.	0.268	0.272	0.270	0.274	0.272	0.267

TABLE 5 - cont'd

DATA

 ρ/t^2 - PRISMS

SPECIMENS	$\rho/t^2 \times 10^{-12}, \text{ kg/m}^3 \text{ sec}^3$	
	335 cycles	427 cycles

A43	0.245	0.240
A44	0.251	0.252
A49	0.226	0.225
A410	0.212	0.202
Ave.	0.233	0.229

C43	0.216	0.215
C44	0.202	0.201
C49	0.207	0.206
C410	0.225	0.224
Ave.	0.212	0.211

CX43	0.211	0.188
CX44	0.212	0.176
CX49	0.189	0.204
CX410	0.205	0.174
Ave.	0.205	0.183

CONTROLS

A42	0.289	0.294
A411	0.294	0.292
A412	0.298	0.293
Ave.	0.294	0.293

C45	0.279	0.288
C411	0.279	0.285
C412	0.280	0.287
Ave.	0.280	0.286

CX45	0.281	0.281
CX411	0.268	0.275
CX412	0.270	0.272
Ave.	0.271	0.276

TABLE 5 - con't

DATA

 ρ/t^2 - PRISMS

SPECIMEN	550 cycles	658 cycles	$\rho/t^2 \times 10^{-9} (\text{kg/m}^3 \text{sec}^2)$		975 cycles
			734 cycles	828 cycles	
A43	0.222	0.215	0.203	0.205	0.201
A44	-	-	-	-	-
A49	0.205	0.207	0.199	0.206	0.202
A410	0.181	0.174	0.172	0.181	0.182
Ave.	<u>0.203</u>	<u>0.199</u>	<u>0.191</u>	<u>0.197</u>	<u>0.195</u>
C43	0.187	0.206	0.187	0.200	0.199
C44	0.190	0.195	0.188	0.202	0.203
C49	0.214	0.217	0.196	0.215	0.211
C410	0.212	0.218	0.197	0.205	0.221
Ave.	<u>0.201</u>	<u>0.209</u>	<u>0.192</u>	<u>0.206</u>	<u>0.209</u>
CX43	0.157	0.140	0.139	0.163	0.160
CX44	-	-	-	-	-
CX49	-	-	-	-	-
CX410	0.167	0.184	0.169	0.188	0.195
Ave.	<u>0.162</u>	<u>0.162</u>	<u>0.154</u>	<u>0.176</u>	<u>0.178</u>
CONTROLS					
A42	0.288	0.297	0.289	0.302	0.307
A411	0.278	0.294	0.292	0.302	0.305
A412	0.297	0.302	0.297	0.352	0.306
Ave.	<u>0.288</u>	<u>0.298</u>	<u>0.293</u>	<u>0.319</u>	<u>0.306</u>
C45	0.293	0.288	0.291	0.290	0.297
C411	0.279	0.291	0.290	0.298	0.294
C412	0.284	0.289	0.288	0.297	0.297
Ave.	<u>0.285</u>	<u>0.289</u>	<u>0.290</u>	<u>0.295</u>	<u>0.296</u>
CX45	0.285	0.288	0.283	0.290	0.284
CX411	0.274	0.270	0.277	0.283	0.286
CX412	0.272	0.269	0.272	0.278	0.280
Ave.	<u>0.277</u>	<u>0.276</u>	<u>0.277</u>	<u>0.284</u>	<u>0.283</u>

TABLE 6
DATA
 $W_A n^2$ - PRISMS

SPECIMENS	$W_A n^2 \times 10^{-7}, \text{ kg/Hz}^2$					
	0 cycles	27 cycles	53 cycles	119 cycles	204 cycles	265 cycles
A43	2.050	1.961	1.969	1.915	1.785	1.878
A44	2.136	2.022	2.009	1.884	1.841	1.872
A49	1.978	1.911	1.838	1.658	1.665	1.583
A410	2.149	1.943	1.895	1.793	1.607	1.571
Ave.	2.077	1.959	1.928	1.808	1.723	1.723
C43	1.967	1.882	1.836	1.753	1.569	1.639
C44	1.908	1.833	1.705	1.547	1.490	1.521
C49	2.118	1.883	1.776	1.617	1.557	1.566
C410	2.061	1.796	1.767	1.633	1.613	1.735
Ave.	2.013	1.849	1.771	1.636	1.557	1.614
CX43	1.956	1.709	1.879	1.694	-	1.643
CX44	1.880	1.780	1.847	1.690	-	1.601
CX47	1.897	1.772	1.857	1.549	-	1.484
CX410	1.992	1.906	1.835	1.759	-	1.507
Ave.	1.932	1.791	1.854	1.673	-	1.559
CONTROLS						
A42	2.069	2.065	2.019	2.090	2.078	2.135
A411	2.045	2.090	2.086	2.217	2.082	2.064
A412	2.226	2.338	2.321	2.347	2.351	2.221
Ave.	2.113	2.161	2.139	2.216	2.169	2.139
C45	1.961	2.046	2.017	2.041	1.948	2.139
C411	2.067	2.018	2.126	2.174	2.045	2.173
C412	2.126	2.026	2.059	2.071	1.971	2.136
Ave.	2.051	2.028	2.066	2.096	1.987	2.150
CX45	1.945	1.998	2.023	2.020	1.946	2.053
CX411	1.937	1.845	1.912	1.949	1.878	1.821
CX412	1.956	1.956	1.945	1.920	1.911	2.013
Ave.	1.947	1.943	1.957	1.963	1.911	1.961

TABLE 6 - cont'd

DATA

 $W_A n^2$ - PRISMS

SPECIMEN	$W_A n^2 \times 10^{-7}, \text{kg.Hz}^2$	
	335 cycles	427 cycles
A43	1.652	1.646
A44	1.709	1.704
A49	1.467	1.455
A410	1.449	1.431
Ave.	1.563	1.557
C43	1.594	1.537
C44	1.423	1.408
C49	1.574	1.565
C410	1.619	1.634
Ave.	1.551	1.535
CX43	1.405	1.256
CX44	1.456	1.330
CX49	1.303	1.168
CX410	1.237	1.037
Ave.	1.349	1.195
CONTROLS		
A42	2.100	2.107
A411	2.141	2.287
A412	2.391	2.263
Ave.	2.209	2.219
C45	1.960	1.910
C411	2.150	2.162
C412	2.129	2.092
Ave.	2.080	2.052
CX45	2.083	2.010
CX411	1.919	1.932
CX412	1.992	2.009
Ave.	1.996	1.985

TABLE 6 - con't

DATA

 $W_A n^2$ - PRISMS

SPECIMEN	$W_A n^2 \times 10^{-10}$ (KgH ₇ ⁻³)				
	550 cycles	658 cycles	734 cycles	828 cycles	975 cycles
A43	1.57	1.52	1.53	1.20	1.53
A44	-	-	-	-	-
A49	0.94	1.11	1.18	-	1.19
A410	1.39	1.32	1.31	1.44	1.30
Ave.	1.30	1.32	1.34	1.32	1.34
C43	1.51	1.52	1.57	1.64	1.62
C44	1.23	-	1.41	1.27	1.20
C49	1.50	1.49	1.54	1.58	1.47
C410	1.65	1.68	1.76	1.89	1.65
Ave.	1.47	1.56	1.57	1.60	1.49
CX43	1.18	1.22	1.10	1.11	1.18
CX44	-	-	-	-	-
CX49	-	-	-	-	-
CX410	1.15	1.25	1.15	-	1.26
Ave.	1.17	1.24	1.12	1.11	1.22
CONTROLS					
A42	2.15	2.25	2.25	2.31	2.24
A411	2.20	2.14	2.22	2.21	2.32
A412	2.34	2.36	2.46	2.37	2.43
Ave.	2.23	2.25	2.31	2.30	2.33
C45	2.06	2.10	2.11	2.08	2.10
C411	2.08	2.16	2.17	2.16	2.19
C412	2.17	2.13	2.24	2.20	2.09
Ave.	2.11	2.13	2.17	2.15	2.13
CX45	2.01	2.03	2.12	2.05	2.14
CX411	1.94	1.96	1.90	1.97	1.99
CX412	1.94	1.99	1.91	1.95	2.00
Ave.	1.96	2.00	1.98	1.99	2.04

TABLE 7
WEIGHT IN AIR - CYLINDERS

DATA

SPECIMEN	WEIGHT IN AIR (grams)			% Change compared to original	
	0 cycles	28 cycles	54 cycles	28 cycles	54 cycles
A32	13705	13598	13566	-0.8	-1.0
A33	13779	13669	13633	-0.8	-1.1
A34	13784	13664	13636	-0.9	-1.1
A35	13709	13577	13531	-1.0	-1.3
Ave.	13744	13627	13591	-0.9	-1.1
C33	13859	13690	13629	-1.2	-1.7
C34	13809	13611	13550	-1.4	-1.9
C36	13852	13646	13595	-1.5	-1.9
C38	13883	13710	13646	-1.2	-1.7
Ave.	13851	13664	13605	-1.3	-1.8
CX31	13878	13815	13808	-0.5	-0.5
CX35	13705	13643	13641	-0.5	-0.5
CX36	13664	13615	13614	-0.4	-0.4
CX37	13781	13738	13745	-0.3	-0.3
Ave.	13757	13703	13702	-0.4	-0.4
CONTROLS					
A31	13784	13783	13782	0.0	0.0
A37	13704	13715	13714	0.1	0.1
Ave.	13744	13749	13748	0.1	0.0
C32	13821	13819	13817	0.0	0.0
C37	13683	13681	13681	0.0	0.0
Ave.	13752	13750	13749	0.0	0.0
CX34	13696	13693	13692	0.0	0.0
CX38	13800	13798	13797	0.0	0.0
Ave.	13748	13746	13745	0.0	0.0

TABLE 7 - cont'd
WEIGHT IN AIR - CYLINDERS

DATA

SPECIMEN	WEIGHT IN AIR (grams)			% Change compared to original		
	119 cycles	203 cycles	265 cycles	119 cycles	203 cycles	265 cycles
A32	13452	13379	13419	-1.8	-2.4	-2.1
A33	13515	13433	13472	-1.9	-2.5	-2.2
A34	13512	13440	13470	-2.0	-2.5	-2.3
A35	13401	13343	13377	-2.2	-2.7	-2.4
Ave.	13470	13399	13435	-2.0	-2.5	-2.2
C33	13487	13421	13491	-2.7	-3.2	-2.7
C34	13407	13355	13465	-2.9	-3.3	-2.5
C36	13457	13399	13500	-2.9	-3.3	-2.5
C38	13509	13438	13503	-2.7	-3.2	-2.7
Ave.	13465	13403	13490	-2.8	-3.2	-2.6
CX31	13744	13724	13856	-1.0	-1.1	-0.2
CX35	13593	13593	13749	-0.8	-0.8	0.3
CX36	13553	13531	13650	-0.8	-1.0	0.0
CX37	13696	13671	13771	-0.3	-0.8	-0.1
Ave.	13647	13630	13759	-0.8	-0.9	0.0
CONTROLS						
A31	13760	13750	13782	-0.2	-0.2	0.0
A37	13693	13686	13720	-0.1	-0.1	0.1
Ave.	13727	13718	13751	-0.1	-0.2	0.1
C32	13799	13770	13801	-0.2	-0.4	-0.1
C37	13657	13632	13666	-0.2	-0.4	-0.1
Ave.	13728	13701	13734	-0.2	-0.4	-0.1
CX34	13663	13646	13679	-0.2	-0.4	-0.1
CX38	13775	13757	13784	-0.2	-0.3	-0.3
Ave.	13719	13702	13732	-0.2	-0.3	-0.1

TABLE 7 - cont'd

DATA

WEIGHT IN AIR - CYLINDERS

SPECIMEN	WEIGHT IN AIR (g)		%Change compared to original	
	335 cycles	427 cycles	335 cycles	427 cycles
A32	13382	13338	-2.4	-2.7
A33	13434	13391	-2.5	-2.8
A34	13429	13384	-2.6	-2.9
A35	13344	13298	-2.7	-3.0
Ave.	13397	13353	-2.5	-2.8
C33	13464	13430	-2.9	-3.1
C34	13433	13404	-2.7	-2.9
C36	13465	13436	-2.8	-3.0
C38	13466	13435	-3.0	-3.2
Ave.	13457	13426	-2.8	-3.1
CX31	13854	13834	-0.2	-0.3
CX35	13745	13721	0.3	+0.1
CX36	13651	13624	-0.1	-0.3
CX37	13762	13736	-0.1	-0.3
Ave.	13753	13729	0.0	-0.2
CONTROLS				
A31	13794	13798	0.1	0.1
A37	13735	13738	0.2	0.2
Ave.	13765	13768	0.2	0.2
C32	13805	13807	-0.1	-0.1
C37	13667	13678	-0.1	0.0
Ave.	13736	13743	-0.1	-0.1
CX34	13689	13699	-0.1	0.0
CX38	13795	13801	0.0	0.0
Ave.	13742	13750	0.0	0.0

TABLE 7 - con't

DATA

WEIGHT IN AIR - CYLINDERS

SPECIMEN	WEIGHT IN AIR (g)			%CHANGE COMPARED TO ORIGINAL		
	550 cycles	658 cycles	734 cycles	550 cycles	658 cycles	734 cycles
A32	-	-	-	-	-	-
A33	13353	13334	13333	-3.1	-3.2	-3.2
A34	13328	13305	13311	-3.3	-3.5	-3.4
A35	13261	13227	13237	-3.3	-3.5	-3.4
Ave.	13314	13289	13294	-3.2	-3.4	-3.3
C33	13402	13398	13420	-3.3	-3.3	-3.2
C34	13414	13413	13436	-2.9	-2.9	-2.7
C36	13424	13428	13448	-3.1	-3.1	-2.9
C38	-	-	-	-	-	-
Ave.	13413	13413	13435	-3.1	-3.1	-2.9
CX31	13839	13836	13851	-0.3	-0.3	-0.2
CX35	-	-	-	-	-	-
CX36	13581	-	13562	-0.6	-	-0.7
CX37	13723	13663	13668	-0.4	-0.9	-0.8
Ave.	13714	13750	13694	-0.4	-0.6	-0.6
CONTROLS						
A31	13805	13811	13824	0.2	0.2	0.3
A37	13742	13751	13760	0.3	0.3	0.4
Ave.	13774	13781	13792	0.3	0.3	0.4
C32	13814	13822	13829	0.0	0.0	0.1
C37	13687	13694	13701	0.0	0.1	0.1
Ave.	13751	13758	13765	0.0	0.1	0.1
CX34	13693	13701	13706	0.0	0.0	0.1
CX37	13804	13809	13818	0.0	0.1	0.1
Ave.	13749	13755	13762	0.0	0.1	0.1

TABLE 7 - con't

DATA

WEIGHT IN AIR - CYLINDERS

SPECIMEN	WEIGHT IN AIR (g)		%CHANGE COMPARED TO ORIGINAL	
	828 cycles	975 cycles	828 cycles	975 cycles
A32	-	-	-	-
A33	13332	13321	-3.2	-3.3
A34	13310	13315	-3.4	-3.4
A35	13245	13237	-3.4	-3.4
Ave.	13296	13291	-3.4	-3.4
C33	13412	13401	-3.2	-3.3
C34	13432	13412	-2.7	-2.9
C36	13453	13426	-2.9	-3.1
C38	-	-	-	-
Ave.	13432	13413	-3.0	-3.1
CX31	13823	13787	-0.4	-0.6
CX35	-	-	-	-
CX36	13539	13472	-0.9	-1.4
CX37	13654	13603	-0.9	-1.3
Ave.	13672	13621	-0.7	-1.1
CONTROLS				
A31	13815	13803	0.2	0.3
A37	13762	13771	0.4	0.5
Ave.	13789	13787	0.3	0.4
C32	13826	13838	0.0	0.1
C37	13701	13710	0.1	0.2
Ave.	13764	13774	0.1	0.2
CX34	13707	13714	0.1	0.1
CX38	13818	13822	0.1	0.2
Ave.	13763	13768	0.1	0.2

TABLE 8

DATA

WEIGHT UNDER WATER - CYLINDERS

SPECIMEN	WEIGHT UNDER WATER (grams)			% Change compared to original	
	0 cycles	28 cycles	54 cycles	28 cycles	54 cycles
A32	7869	7764	7733	-1.3	-1.7
A33	7945	7838	7802	-1.3	-1.8
A34	7946	7832	7798	-1.4	-1.9
A35	7901	7769	7728	-1.7	-2.2
Ave.	7915	7801	7765	-1.4	-1.9
C33	8059	7896	7835	-2.0	-2.8
C34	8011	7815	7758	-2.4	-3.2
C36	8019	7823	7771	-2.4	-3.1
C38	8072	7903	7844	-2.1	-2.8
Ave.	8040	7859	7802	-2.2	-3.0
CX31	8071	8013	8003	-0.7	-0.8
CX35	7913	7855	7855	-0.7	-0.7
CX36	7835	7838	7840	-0.6	-0.6
CX37	7961	7924	7931	-0.5	-0.4
Ave.	7958	7908	7904	-0.6	-0.7
CONTROLS					
A31	7951	7959	7957	0.1	0.1
A37	7912	7922	7923	0.1	0.1
Ave.	7932	7941	7940	0.1	0.1
C32	8037	8042	8039	0.1	0.0
C37	7901	7905	7901	0.1	0.0
Ave.	7969	7974	7970	0.1	0.0
CX34	7896	7902	7898	0.1	0.0
CX38	7913	7996	7995	1.0	1.0
Ave.	7905	7949	7947	0.6	0.5

TABLE 8 - cont'd

DATA

WEIGHT UNDER WATER - CYLINDERS

SPECIMEN	WEIGHT UNDER WATER (grams)			% Change compared to original		
	119 cycles	203 cycles	265 cycles	119 cycles	203 cycles	265 cycles
A32	7631	7575	7579	-3.0	-3.7	-3.7
A33	7697	7636	7636	-3.1	-3.9	-3.9
A34	7697	7634	7631	-3.1	-3.9	-4.0
A35	7613	7561	7572	-3.6	-4.3	-4.2
Ave.	7660	7602	7605	-3.2	-4.0	-3.9
C33	7709	7652	7694	-4.3	-5.1	-4.5
C34	7636	7592	7661	-4.7	-5.2	-4.4
C36	7653	7602	7667	-4.6	-5.2	-4.4
C38	7724	7660	7693	-4.3	-5.1	-4.7
Ave.	7681	7627	7679	-4.5	-5.1	-4.5
CX31	7955	7949	8047	-1.4	-1.5	-0.3
CX35	7820	7827	7955	-1.2	-1.1	0.5
CX36	7797	7783	7877	-1.1	-1.3	-0.1
CX37	7902	7836	7950	-0.7	-0.9	-0.1
Ave.	7869	7861	7957	-1.1	-1.2	0.0
CONTROLS						
A31	7953	7943	7942	0.0	-0.1	-0.1
A37	7918	7910	7913	0.1	0.0	0.0
Ave.	7936	7927	7928	0.1	-0.1	-0.1
C32	8031	8010	8003	-0.1	-0.3	-0.4
C37	7891	7874	7872	-0.1	-0.3	-0.4
Ave.	7961	7942	7938	-0.1	-0.3	-0.4
CX34	7891	7876	7873	-0.1	-0.3	-0.3
CX38	7985	7968	7969	0.9	0.7	0.7
Ave.	7938	7922	7921	0.4	0.2	0.2

TABLE 8 - cont'd

DATA

WEIGHT UNDER WATER - CYLINDERS

SPECIMEN	WEIGHT UNDER WATER (g)		% Change compared to original	
	335 cycles	427 cycles	335 cycles	427 cycles
A32	7547	7509	-4.1	-4.6
A33	7604	7561	-4.3	-4.8
A34	7595	7546	-4.4	-5.0
A35	7537	7499	-4.6	-5.1
Ave.	7571	7529	-4.3	-4.9
C33	7674	7640	-4.8	-5.2
C34	7638	7614	-4.7	-5.0
C36	7637	7608	-4.8	-5.1
C38	7660	7628	-5.1	-5.5
Ave.	7652	7623	-4.8	-5.2
CX31	8051	8031	-0.2	-0.5
CX35	7954	7933	0.5	0.3
CX36	7875	7847	-0.1	-0.5
CX37	7947	7920	-0.2	-0.5
Ave.	7957	7933	0.0	-0.3
CONTROLS				
A31	7962	7963	0.1	0.2
A37	7934	7935	0.3	0.3
Ave.	7948	7949	0.2	0.2
C32	8022	8020	-0.2	-0.2
C37	7886	7890	-0.2	-0.1
Ave.	7954	7955	-0.2	-0.2
CX34	7894	7895	0.0	0.0
CX38	7989	7992	1.0	1.0
Ave.	7942	7944	0.5	0.5

TABLE 8 - con't

DATA

WEIGHT UNDER WATER - CYLINDERS

SPECIMEN	WEIGHT UNDER WATER (g)			%CHANGE COMPARED TO ORIGINAL		
	550 cycles	658 cycles	734 cycles	550 cycles	658 cycles	734 cycles
A32	-	-	-	-	-	-
A33	7522	7500	7504	-5.3	-5.6	-5.6
A34	7496	7470	7476	-5.7	-6.0	-5.9
A35	7457	7422	7435	-5.6	-6.1	-5.9
Ave.	7492	7464	7472	-5.5	-5.9	-5.8
C33	7601	7604	7781	-5.7	-5.7	-3.4
C34	7624	7613	7643	-4.8	-5.0	-4.6
C36	7585	7598	7618	-5.4	-5.3	-5.0
C38	-	-	-	-	-	-
Ave.	7603	7605	7681	-5.3	-5.3	-4.3
CX31	8037	8027	8044	-0.4	-0.6	-0.3
CX35	-	-	-	-	-	-
CX36	7818	-	7802	-0.9	-	-1.1
CX37	7897	7869	7877	-0.8	-1.2	-1.1
Ave.	7917	7948	7908	-0.7	-0.9	-0.6
CONTROLS						
A31	7970	7976	7988	0.2	0.3	0.5
A37	7937	7945	7961	0.3	0.0	0.6
Ave.	7954	7961	7975	0.3	0.2	0.6
C32	8032	8034	8046	0.0	0.0	0.1
C37	7903	7905	7916	0.0	0.0	0.2
Ave.	7968	7970	7981	0.0	0.0	0.2
CX34	7902	7903	7906	0.1	0.0	0.1
CX38	7997	7997	8011	1.1	1.1	1.2
Ave.	7950	7950	7959	0.6	0.6	0.7

TABLE 8 - con't

DATA

WEIGHT UNDER WATER - CYLINDERS

SPECIMEN	WEIGHT UNDER WATER (g)		%CHANGE COMPARED TO ORIGINAL	
	828 cycles	975 cycles	828 cycles	975 cycles
A32	-	-	-	-
A33	7504	7489	-5.6	-5.7
A34	7480	7477	-5.9	-5.9
A35	7444	7431	-5.8	-6.0
Ave.	<u>7476</u>	<u>7466</u>	<u>-5.7</u>	<u>-5.9</u>
C33	7621	7604	-	-5.7
C34	7633	7611	-4.7	-5.0
C36	7626	7601	-4.9	-5.2
C38	-	-	-	-
Ave.	<u>7627</u>	<u>7605</u>	<u>-4.8</u>	<u>-5.3</u>
CX31	8023	7998	-0.6	-0.9
CX35	-	-	-	-
CX36	7784	7740	-1.3	-1.8
CX37	<u>7866</u>	<u>7830</u>	<u>-1.2</u>	<u>-1.7</u>
Ave.	<u>7891</u>	<u>7856</u>	<u>-1.0</u>	<u>-1.5</u>
CONTROLS				
A31	7983	7989	0.4	0.5
A37	7962	7962	0.6	0.6
Ave.	<u>7973</u>	<u>7976</u>	<u>0.5</u>	<u>0.6</u>
C32	8040	8045	0.0	0.1
C37	7916	7920	0.2	0.2
Ave.	<u>7978</u>	<u>7983</u>	<u>0.1</u>	<u>0.2</u>
CX34	7909	7908	0.2	0.2
CX38	8008	8005	1.2	1.2
Ave.	<u>7959</u>	<u>7957</u>	<u>0.7</u>	<u>0.7</u>

TABLE 9

DATA

VOLUMES OF CYLINDERS

SPECIMEN	VOLUME (cm ³)			% Change compared to original	
	0 cycles	28 cycles	54 cycles	28 cycles	54 cycles
A32	5841	5839	5838	-0.03	-0.05
A33	5839	5836	5836	-0.05	-0.05
A34	5843	5837	5843	-0.10	0.00
A35	5813	5813	5808	0.00	-0.09
Ave.	5835	5832	5832	-0.05	-0.05
C33	5805	5799	5799	-0.10	-0.10
C34	5803	5801	5797	-0.03	-0.10
C36	5838	5828	5829	-0.17	-0.15
C38	5816	5812	5807	-0.07	-0.15
Ave.	5816	5811	5809	-0.09	-0.12
CX31	5812	5807	5810	-0.09	-0.03
CX35	5797	5793	5791	-0.07	-0.10
CX36	5784	5782	5779	-0.03	-0.09
CX37	5825	5819	5819	-0.10	-0.10
Ave.	5805	5801	5801	-0.07	-0.07
CONTROLS					
A31	5838	5829	5830	-0.15	-0.14
A37	5797	5798	5796	0.02	-0.02
Ave.	5818	5814	5814	-0.07	-0.07
C32	5789	5782	5783	-0.12	-0.10
C37	5787	5781	5785	-0.10	-0.03
Ave.	5789	5782	5785	-0.12	-0.07
CX34	5805	5796	5799	-0.16	-0.10
CX38	5892	5807	5807	-1.44	-1.44
Ave.	5849	5802	5804	-0.80	-0.77

TABLE 9 - cont'd

DATA

VOLUMES OF CYLINDERS

SPECIMEN	VOLUME (cm ³)			% Change compared to original		
	119 cycles	203 cycles	265 cycles	119 cycles	203 cycles	265 cycles
A32	5826	5809	5842	-0.26	-0.55	0.02
A33	5823	5802	5838	-0.27	-0.63	-0.02
A34	5820	5811	5841	-0.39	-0.55	-0.03
A35	5793	5787	5807	-0.34	-0.45	-0.10
Ave.	5816	5803	5833	-0.33	-0.55	-0.03
C33	5783	5774	5799	-0.38	-0.53	-0.10
C34	5776	5768	5806	-0.47	-0.60	0.05
C36	5809	5802	5835	-0.50	-0.62	-0.05
C38	5790	5783	5812	-0.45	-0.57	-0.07
Ave.	5790	5783	5814	-0.45	-0.57	-0.03
CX31	5794	5780	5811	-0.31	-0.55	-0.02
CX35	5778	5771	5796	-0.31	-0.45	-0.02
CX36	5761	5753	5785	-0.40	-0.54	0.02
CX37	5799	5790	5823	-0.45	-0.60	-0.03
Ave.	5784	5774	5805	-0.36	-0.53	0.00
CONTROLS						
A31	5812	5812	5842	-0.45	-0.45	0.07
A37	5780	5781	5809	-0.29	-0.28	0.21
Ave.	5797	5797	5826	-0.36	-0.36	0.14
C32	5773	5765	5800	-0.28	-0.41	0.19
C37	5771	5763	5796	-0.28	-0.41	0.16
Ave.	5773	5765	5799	-0.28	-0.41	0.17
CX34	5777	5775	5808	-0.48	-0.52	0.05
CX38	5795	5794	5817	-1.65	-1.66	-1.27
Ave.	5787	5785	5813	-1.06	-1.09	-0.62

TABLE 9 - cont'd
VOLUMES OF CYLINDERS

DATA

SPECIMEN	VOLUME (cm ³)		% Change compared to original	
	335 cycles	427 cycles	335 cycles	427 cycles
A32	5839	5837	-0.03	-0.07
A33	5834	5838	-0.09	-0.02
A34	5838	5846	-0.09	0.05
A35	5811	5807	-0.03	-0.10
Ave.	5831	5832	-0.07	-0.05
C33	5794	5798	-0.19	-0.12
C34	5799	5798	-0.07	-0.09
C36	5832	5836	-0.10	-0.03
C38	5810	5815	-0.10	-0.02
Ave.	5809	5812	-0.12	-0.07
CX31	5807	5811	-0.09	-0.02
CX35	5795	5796	-0.03	-0.02
CX36	5780	5785	-0.07	0.02
CX37	5819	5824	-0.10	-0.02
Ave.	5801	5804	-0.07	-0.02
CONTROLS				
A31	5837	5843	-0.02	0.09
A37	5806	5811	0.16	0.16
Ave.	5822	5827	0.07	0.15
C32	5788	5795	-0.02	0.10
C37	5786	5796	-0.02	0.16
Ave.	5788	5796	-0.02	0.12
CX34	5800	5812	-0.09	0.12
CX38	5811	5817	-1.37	-1.27
Ave.	5806	5815	-0.74	-0.58

TABLE 9 - con't
VOLUME - CYLINDERS

DATA

SPECIMEN	VOLUME (cm ³)			%CHANGE COMPARED TO ORIGINAL		
	550 cycles	658 cycles	734 cycles	550 cycles	658 cycles	734 cycles
A32	-	-	-	-	-	-
A33	5846	5844	5843	0.0	0.1	0.1
A34	5847	5845	5849	0.0	0.1	0.1
A35	5819	5814	5816	0.1	0.1	0.1
Ave.	5837	5835	5836	0.0	0.1	0.1
C33	5801	5804	-	0.0	0.1	-
C34	5790	5810	5807	-0.2	0.1	0.1
C36	5839	5840	5844	0.4	0.1	0.1
C38	-	-	-	-	-	-
Ave.	5810	5818	5828	0.1	0.1	0.1
CX31	5802	5819	5821	-0.2	0.1	0.2
CX35	-	-	-	-	-	-
CX36	5763	-	5774	-0.4	-	-0.2
CX37	5826	5804	5805	0.0	-0.4	-0.3
Ave.	5797	5812	5800	-0.2	-0.2	-0.1
CONTROLS						
A31	5835	5845	5851	0.0	0.1	0.2
A37	5805	5816	5814	0.7	0.3	0.3
Ave.	5820	5831	5833	0.4	0.2	0.3
C32	5782	5798	5798	-0.1	0.0	0.2
C37	5784	5799	5800	-0.1	0.2	0.2
Ave.	5783	5799	5799	-0.1	0.1	0.2
CX34	5791	5808	5815	-0.2	0.1	0.3
CX38	5807	5822	5822	-1.4	-1.2	-1.2
Ave.	5799	5815	5819	-0.8	-0.6	-0.5

TABLE 9 - con't

DATA

VOLUME - CYLINDERS

SPECIMEN	VOLUME (cm ³)		% CHANGE COMPARED TO ORIGINAL	
	828 cycles	975 cycles	828 cycles	975 cycles
A32	-	-	-	-
A33	5846	5846	0.1	0.2
A34	5848	5852	0.1	0.2
A35	5819	5820	0.1	0.2
Ave.	5838	5839	0.1	0.2
C33	5809	5811	-	0.2
C34	5817	5815	0.2	0.3
C36	5845	5839	0.1	0.1
C38	-	-	-	-
Ave.	5824	5822	0.2	0.2
CX31	5818	5803	0.1	-0.1
CX35	-	-	-	-
CX36	5773	5746	-0.2	-0.6
CX37	5806	5787	-0.3	-0.6
Ave.	5799	5779	-0.1	-0.4
CONTROLS				
A31	5850	5855	0.2	0.4
A37	5818	5823	0.4	0.5
Ave.	5834	5839	0.3	0.4
C32	5804	5807	0.3	0.4
C37	5803	5804	0.3	0.4
Ave.	5804	5806	0.3	0.4
CX34	5816	5820	0.2	0.3
CX38	5828	5831	-1.1	-1.0
Ave.	5822	5826	-0.5	-0.3

TABLE 10
DENSITY MEASUREMENTS - CYLINDERS

DATA

SPECIMEN	DENSITY, kg/m^3			% Change compared to original	
	0 cycles	28 cycles	54 cycles	28 cycles	54 cycles
A32	2346	2328	2323	-0.8	-1.0
A33	2359	2342	2336	-0.7	-1.0
A34	2359	2341	2333	-0.8	-1.1
A35	2358	2335	2329	-1.0	-1.2
Ave.	<u>2356</u>	<u>2337</u>	<u>2330</u>	<u>-0.8</u>	<u>-1.1</u>
C33	2387	2360	2350	-1.1	-1.6
C34	2379	2346	2337	-1.4	-1.8
C36	2372	2341	2332	-1.3	-1.7
C38	2387	2359	2350	-1.2	-1.6
Ave.	<u>2381</u>	<u>2351</u>	<u>2342</u>	<u>-1.3</u>	<u>-1.6</u>
CX31	2387	2379	2376	-0.3	-0.5
CX35	2364	2355	2355	-0.4	-0.4
CX36	2362	2354	2355	-0.3	-0.3
CX37	2366	2361	2362	-0.2	-0.2
Ave.	<u>2370</u>	<u>2362</u>	<u>2362</u>	<u>-0.3</u>	<u>-0.3</u>
CONTROLS					
A31	2361	2364	2364	0.1	0.1
A37	2364	2365	2366	0.0	0.1
Ave.	<u>2363</u>	<u>2365</u>	<u>2365</u>	<u>0.1</u>	<u>0.1</u>
C32	2412	2390	2389	-0.9	-1.0
C37	2364	2366	2365	0.1	0.0
Ave.	<u>2388</u>	<u>2378</u>	<u>2377</u>	<u>-0.4</u>	<u>-0.5</u>
CX34	2359	2362	2361	0.1	0.1
CX38	2342	2376	2376	1.5	1.5
Ave.	<u>2351</u>	<u>2369</u>	<u>2368</u>	<u>0.8</u>	<u>0.7</u>

TABLE 10 - cont'd

DATA

DENSITY MEASUREMENTS - CYLINDERS

SPECIMEN	DENSITY, kg/m ³			% Change compared to original		
	119 cycles	203 cycles	265 cycles	119 cycles	203 cycles	265 cycles
A32	2308	2303	2296	-1.6	-1.8	-2.1
A33	2320	2331	2307	-1.7	-1.2	-2.2
A34	2321	2313	2305	-1.6	-1.9	-2.3
A35	2312	2305	2303	-2.0	-2.2	-2.3
Ave.	2316	2309	2303	-1.7	-2.0	-2.2
C33	2331	2324	2326	-2.3	-2.6	-2.6
C34	2320	2315	2318	-2.5	-2.7	-2.6
C36	2316	2309	2313	-2.4	-2.7	-2.5
C38	2322	2323	2322	-2.3	-2.7	-2.7
Ave.	2325	2318	2320	-2.4	-2.8	-2.6
CX31	2371	2374	2384	-0.7	-0.5	-0.1
CX35	2352	2355	2371	-0.5	-0.4	0.3
CX36	2352	2352	2360	-0.4	-0.4	-0.1
CX37	2361	2361	2364	-0.2	-0.2	-0.1
Ave.	2359	2360	2370	-0.5	-0.4	0.0
CONTROLS						
A31	2367	2365	2358	0.3	0.2	-0.1
A37	2368	2367	2361	0.2	0.1	-0.1
Ave.	2368	2366	2360	0.2	0.1	-0.1
C32	2389	2388	2379	-1.0	-1.0	-1.4
C37	2366	2365	2357	0.1	0.0	-0.3
Ave.	2378	2377	2368	-0.4	-0.5	-0.8
CX34	2364	2363	2354	0.2	0.2	-0.2
CX38	2376	2374	2369	1.5	1.4	1.2
Ave.	2371	2368	2362	0.9	0.7	0.5

TABLE 10 - cont'd DATA
DENSITY MEASUREMENTS - CYLINDERS

SPECIMEN	DENSITY, kg/m ³		% Change compared to original	
	335 cycles	427 cycles	335 cycles	427 cycles
A32	2291	2285	-2.3	-2.6
A33	2302	2293	-2.4	-2.8
A34	2300	2289	-2.5	-3.0
A35	2296	2289	-2.6	-2.9
Ave.	2298	2290	-2.5	-2.8
C33	2323	2316	-2.7	-3.0
C34	2316	2311	-2.6	-2.9
C36	2308	2302	-2.7	-3.0
C38	2317	2310	-2.9	-3.2
Ave.	2316	2310	-2.7	-3.0
CX31	2385	2380	-0.1	-0.3
CX35	2371	2367	0.3	0.1
CX36	2361	2355	0.0	-0.3
CX37	2364	2358	-0.1	-0.3
Ave.	2371	2365	0.0	-0.2
CONTROLS				
A31	2362	2361	0.0	0.0
A37	2365	2364	0.0	0.0
Ave.	2364	2363	0.0	0.0
C32	2384	2382	-1.2	-1.2
C37	2361	2359	-0.1	-0.2
Ave.	2373	2371	-0.6	-0.7
CX34	2359	2356	0.0	-0.1
CX38	2373	2372	1.3	1.3
Ave.	2367	2365	0.7	0.9

TABLE 10 - con't

DATA

DENSITY - CYLINDERS

SPECIMEN	DENSITY (kg/m ³)			%CHANGE COMPARED TO ORIGINAL		
	550 cycles	658 cycles	734 cycles	550 cycles	658 cycles	734 cycles
A32	-	-	-	-	-	-
A33	2284	2282	2282	-2.6	-3.3	-3.3
A34	2279	2276	2276	-3.4	-3.6	-3.5
A35	2279	2275	2276	-3.4	-3.5	-3.5
Ave.	2281	2278	2278	-3.1	-3.5	-3.4
C33	2310	2308	2374	-3.2	-3.3	-0.5
C34	2317	2309	2314	-2.6	-2.9	-2.7
C36	2299	2299	2301	-3.1	-3.1	-3.0
C38	-	-	-	-	-	-
Ave.	2309	2305	2330	-3.0	-3.1	-2.1
CX31	2385	2378	2379	0.0	0.0	-0.4
CX35	-	-	-	-	-	-
CX36	2357	-	2349	-0.2	-	-0.6
CX37	2356	2354	2354	-0.4	-0.5	-0.5
Ave.	2366	2366	2361	-0.2	-0.3	-0.5
CONTROLS						
A31	2366	2363	2363	-0.2	0.1	0.1
A37	2367	2364	2367	0.1	0.0	0.1
Ave.	2367	2364	2365	0.0	0.1	0.1
C32	2389	2384	2385	-0.1	-1.2	-1.1
C37	2366	2361	2362	0.1	0.0	-0.1
Ave.	2378	2373	2374	0.0	-0.6	-0.6
CX34	2365	2359	2357	0.3	0.0	-0.1
CX38	2377	2372	2373	1.5	1.3	1.3
Ave.	2371	2366	2365	0.9	0.7	0.6

TABLE 10 - con't

DATA

DENSITY - CYLINDERS

SPECIMEN	DENSITY (kg/m ³)		%CHANGE COMPARED TO ORIGINAL	
	828 cycles	975 cycles	828 cycles	975 cycles
A32	-	-	-	-
A33	2281	2279	-3.3	-3.5
A34	2276	2275	-3.5	-3.6
A35	2276	2274	-3.5	-3.6
Ave.	2278	2276	-3.4	-3.6
C33	2309	2306	-	-3.4
C34	2309	2306	-2.9	-3.1
C36	2302	2299	-3.0	-3.1
C38	-	-	-	-
Ave.	2307	2304	-3.0	-3.2
CX31	2376	2376	-0.5	-0.5
CX35	-	-	-	-
CX36	2345	2345	-0.7	-0.8
CX37	2352	2351	-0.6	-0.7
Ave.	2358	2357	-0.6	-0.7
CONTROLS				
A31	2361	2362	0.0	-0.0
A37	2365	2365	0.1	0.0
Ave.	2363	2364	0.0	0.0
C32	2382	2383	-1.2	-1.3
C37	2361	2362	-0.1	-0.1
Ave.	2372	2373	-0.7	-0.7
CX34	2357	2356	-0.1	-0.2
CX38	2371	2371	1.2	1.2
Ave.	2364	2364	0.6	0.5

TABLE 11
 ρ/t^2 - CYLINDERS

DATA

SPECIMEN	$\rho/t^2 \times 10^{-12}, \text{ kg/m}^3 \text{ sec}^3$					
	0 cycles	28 cycles	54 cycles	119 cycles	203 cycles	265 cycles
A32	1.70	1.55	1.52	1.55	1.45	1.44
A33	1.73	1.53	1.51	1.52	1.54	1.38
A34	1.72	1.49	1.47	1.57	1.45	1.35
A35	1.69	1.50	1.44	1.54	1.39	1.39
Ave.	1.71	1.52	1.49	1.55	1.45	1.39
C33	1.62	1.52	1.41	1.44	1.34	1.39
C34	1.68	1.45	1.29	1.37	1.39	1.32
C36	1.54	1.45	1.36	1.39	1.32	1.20
C38	1.58	1.43	1.41	1.44	1.42	1.28
Ave.	1.60	1.46	1.37	1.43	1.37	1.30
CX31	1.64	1.52	1.46	1.54	1.37	1.49
CX35	1.50	1.47	1.46	1.47	1.46	1.31
CX36	1.46	1.52	1.42	1.49	1.39	1.39
CX34	1.51	1.51	1.42	1.42	1.37	1.33
Ave.	1.53	1.51	1.44	1.48	1.40	1.33
CONTROLS						
A31	1.58	1.67	1.63	1.69	1.60	1.61
A37	1.73	1.59	1.56	1.72	1.84	1.58
Ave.	1.65	1.63	1.59	1.70	1.71	1.59
C32	1.72	1.76	1.61	1.68	1.67	1.43
C37	1.51	1.56	1.49	1.63	1.58	1.41
Ave.	1.61	1.66	1.55	1.66	1.62	1.42
CX34	1.54	1.54	1.55	1.58	1.55	1.41
CX38	1.49	1.59	1.59	1.61	1.51	1.55
Ave.	1.51	1.56	1.56	1.59	1.53	1.48

TABLE 11 - cont'd

DATA

 ρ/t^2 - CYLINDERS

SPECIMEN	$\rho/t^2 \times 10^{-12}, \text{ kg/m}^3 \text{ sec}^3$	
	335 cycles	427 cycles
A32	1.35	1.40
A33	1.38	1.38
A34	1.32	1.44
A35	1.34	1.25
Ave.	<u>1.35</u>	<u>1.36</u>
C33	1.34	1.29
C34	1.29	1.27
C36	1.31	1.28
C38	1.32	1.28
Ave.	<u>1.32</u>	<u>1.28</u>
CX31	1.38	1.32
CX35	1.34	1.18
CX36	1.35	1.27
CX37	1.29	1.19
Ave.	<u>1.34</u>	<u>1.24</u>
CONTROLS		
A31	1.65	1.64
A37	1.67	1.64
Ave.	<u>1.66</u>	<u>1.64</u>
C32	1.67	1.66
C37	1.61	1.50
Ave.	<u>1.63</u>	<u>1.66</u>
CX34	1.56	1.49
CX38	1.61	1.54
Ave.	<u>1.58</u>	<u>1.52</u>

TABLE 11 - con't

DATA

 ρ/t^2 - CYLINDERS

SPECIMEN	$\rho/t^2 \times 10^{-9} (\text{kg/m}^3 \text{sec}^2)$				
	550 cycles	658 cycles	734 cycles	828 cycles	975 cycles
A32	-	-	-	-	-
A33	1.413	1.371	1.037	1.228	1.053
A34	0.923	1.309	1.203	1.341	1.034
A35	1.330	1.272	1.022	1.220	0.995
Ave.	1.222	1.317	1.087	1.263	1.027
C33	1.335	1.321	1.255	1.251	1.071
C34	1.242	1.215	1.103	1.028	0.915
C36	1.130	1.361	1.162	1.239	1.081
C38	-	-	-	-	-
Ave.	1.236	1.299	1.173	1.173	1.022
CX31	1.255	1.323	1.083	1.297	1.122
CX35	-	-	-	-	-
CX36	1.185	-	0.994	1.057	1.117
CX37	0.993	0.867	0.841	0.908	0.936
Ave.	1.144	1.095	0.972	1.087	1.058
CONTROLS					
A31	1.428	1.654	1.484	1.863	1.697
A37	1.767	1.690	1.748	1.737	1.745
Ave.	1.598	1.672	1.616	1.800	1.721
C32	1.699	1.551	1.742	1.712	1.658
C37	1.621	1.601	1.569	1.679	1.418
Ave.	1.660	1.576	1.656	1.696	1.538
CX34	1.604	1.576	1.624	1.607	1.509
CX38	1.508	1.560	1.593	1.600	1.534
Ave.	1.556	1.564	1.609	1.604	1.522

APPENDIX V

METHOD OF COMPARISON BETWEEN TWO SAMPLE AVERAGES

The technique used to determine if two observed sample averages are identical is outlined below.

The samples to be compared are that for the percent change in weight in air for the prismatic specimens from the wooden and metallic molds. In this example, mix A will be considered. Thus, the two samples are the percent change in weight in air of specimens A43 and A44 after 27, 53, 119, 204, 265, 335 and 427 cycles and the percent change in weight in air of specimens A49 and A410 after the same number of cycles. Specimen A43 and A44 were formed using wooden molds while specimens A49 and A410 were formed from metallic molds.

Thus there were 14 numbers to be averaged for each sample average, leaving 13 degrees of freedom for each sample. The averages and variance were calculated for each sample.

WOODEN MOLDS

$$n_1 = 14$$

$$v_1 = 13$$

$$\bar{Y}_1 = -1.26$$

$$S_1^2 = 0.42$$

METALLIC MOLDS

$$n_2 = 14$$

$$v_2 = 13$$

$$\bar{Y}_2 = -2.01$$

$$S_2^2 = 0.80$$

Two hypothesis were proposed, the null hypothesis being that the two sample means are equivalent.

$$\mu_1 = \mu_2 \quad \text{or} \quad \mu_1 - \mu_2 = 0$$

The alternative hypothesis being that the two sample means are not equivalent.

$$\mu_1 \neq \mu_2 \quad \text{or} \quad \mu_1 - \mu_2 \neq 0$$

The variance for the two samples were pooled:

$$S_p^2 = \frac{13(0.42) + 13(0.80)}{13 + 13} = 0.61$$

The confidence interval for the difference between the two sample means was derived using:

$$(\bar{Y}_1 - \bar{Y}_2) \pm t_{v_1+v_2, \alpha} S_p \left[\frac{1}{n_1} + \frac{1}{n_2} \right]^{1/2}$$

where t is obtained from a standard t -distribution at the 95% confidence level.

Since $t_{26, .05/2} = 2.056$ then

$$(-1.26 + 2.01) \pm 2.056 [0.61(1/14 + 1/14)]^{1/2}$$

Therefore the 95% confidence limit for the differences between the two sample averages is given as:

$$0.14 \quad \text{to} \quad 1.36$$

In this case the alternative hypothesis is valid since zero is not contained within the interval. The results indicate that at the 95% confidence level there exists a significant difference between the sample averages of the specimens cast from wooden molds and from the metallic molds.